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## Windborne debris trajectories in tornado-like flow field initiated from a low-rise building

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6 ABSTRACT: This paper examines compact debris flight in tornado-like flow fields. The 7 research focuses on physically simulating a specific tornado-like vortex and on investigating 8 windborne debris flight with and without a low-rise building model. The low-rise building 9 model, 1/8<sup>th</sup> scale with regard to the vortex core radius, was used to initiate the flight of 10 Styrofoam spheres from its top. Debris motion was recorded using three high-speed cameras and data reduction was performed on open-source OpenPTV software. Flow field 11 12 characterisation showed that including a building model does not considerably affect the averaged flow field but only the local instantaneous flow field. Debris flight analysis shows 13 14 that the mean flight distance is not affected by the building model, but a change in the initial 15 direction occurs. Comparison between local wind flow field and initial debris velocities shows good agreement, and therefore the variability in initial directions of the debris flight can be 16 17 attributed to a wind-driven process. To compare with experimental data, experimental data 18 were incorporated into debris flight equations to compute debris motion. Debris trajectories 19 computed from experimental data show strong visual similarities with experimental trajectories 20 and debris flight analysis presents good agreement with experimental data.

21 KEYWORDS: tornado-like vortex, debris, low-rise building, 3D-PTV.

#### 22 1 INTRODUCTION

23

24 Tornadoes are fast vertical swirling columns of air formed inside a storm and connecting the 25 cloud base and the ground via a funnel cloud. Tornadoes account for the strongest and most 26 devastating natural wind phenomenon with wind speeds up to 480 km/h. When fully developed, 27 the width of a tornado can reach half a mile in diameter and travel long distances. Moreover, 28 the debris cloud during a tornadic event, observable when dust and/or objects are lifted aloft 29 and are swirling around the tornado, can account for twice the size of the tornado itself 30 (Wurman et al., 2013). In 2018, 628 tornadoes were reported in Europe. In the United 31 Kingdom, about 30 tornadoes are reported every year, with 2.2 tornadoes per year per 10,000 32 km sq. on average. This is more than in the U.S. with 1.3 tornadoes per year per 10,000km sq. 33 and about 1,200 tornadoes occurring every year (Mulder and Schultz, 2015). Nevertheless, 34 tornadoes in the U.S. are stronger than tornadoes usually occurring in Europe. As a result, over 35 the last 40 years, about 60 fatalities were reported and billions of dollars of damages are caused 36 every year on U.S. soil. Damage to property and infrastructure due to tornadoes can mainly be 37 attributed to the high wind speeds, the low pressure inside the vortex core and windborne debris (Brooks and Doswell, 2001). Windborne debris embedded during strong wind events, such as 38 39 downbursts, hurricanes or tornadoes, can lead to major wind disasters. When reaching high 40 velocities, debris can significantly damage engineered and non-engineered buildings, resulting in the production of even more debris, known as debris chain (Figure 1). 41



Figure 1 Windborne debris chain (from Kakimpa et al. (2012))

42 Due to their unpredictability and their danger, full-scale tornadoes are difficult to study, 43 therefore it is particularly challenging to obtain in-situ velocity and pressure data. Using 44 Doppler radar measurements, (Wurman and Alexander, 2005) collected wind field measurements of the Spencer South Dakota tornado of May 30, 1998. However, due to the 45 46 earth's curvature and Doppler radar elevation angle, no data are usually obtained below 30m AGL (Wurman et al., 2013), which is usually more than standard low-rise building heights. To 47 overcome this limitation, Bluestein and Unruh (1989) used a Portable Doppler radar to 48 49 intercept and get as close as 10km distance from a tornado. As a result, between 1995 and 2008, 50 150 tornadoes have been measured using Doppler On Wheels (DOWs) (Alexander and Wurman, 2008) with measurements within 20m Above Ground Level (AGL) (Kosiba and 51 52 Wurman, 2013).

53 Recourse to physical modelling of tornadoes has had a significant impact in our understanding of the processes governing tornado-like flow fields. Ward (1972) pioneered the tornado 54 55 generator that could generate realistic tornado-like vortices and sub-vortices. Ward-type 56 generators use guide vanes to introduce angular momentum and an exhaust fan to generate an 57 updraft. Several Ward-type generators were then developed to further investigate tornado-like 58 vortices in small-scale (Church et al., 1977), small/medium scale (Gillmeier et al., 2018) and 59 large-scale generators (Tang et al., 2018). Over the past decades, tornado generators with new design have been developed: Mishra et al. (2008a; 2008b) developed a Ward-type generator 60 61 where the circulation is driven by 16 slotted jets; (Haan et al., 2008) developed a new large-62 scale translating generator with a central exhaust fan and an annular duct recirculating the flow downward; Refan et al. (2014) used the new large-scale 3D wind testing facility (WindEEE 63 64 dome) to generate tornado-like vortices. Through the years and improvements, each generator 65 presented improving similarities with full-scale tornadoes. The pressure drop in the vortex core matched with the 2004 Manchester (U.S.) tornado (Mishra et al., 2008a) and velocity 66 components showed good agreements with full-scale measurements (Haan et al., 2008). 67 68 Tornado-like vortex generators can also model one and two-cell vortices (Haan et al., 2008; 69 Tang et al., 2018), and improved the understanding of the vortex breakdown during the 70 transition between one and two-cell structure (Church and Snow, 1985). However, Baker and 71 Sterling (2019) recently questioned the efficacy of tornado simulators to reproduce full-scale tornadoes. The authors looked at various dimensionless group to evaluate the performance of 72 73 several tornado simulators with regards to dynamic, kinematic and geometric similarities. The

- 74 main conclusion drawn from this analysis is that some are able to match geometric similarity
- for some tornadoes, some are able to match kinematic similarity but none of the current tornado
- simulators are capable to show all similarities with full-scale tornadoes and therefore have
- 77 limited capabilities.

Different analytical vortex models have been developed to reproduce tornado-like flow field (Rankine, 1882; Burgers, 1948; Rott, 1958; Sullivan, 1959; Baker and Sterling, 2017). However, due to the assumptions made and the complexity of tornado flow fields, some vortex models tend to only reproduce the tangential velocity component correctly and remain incapable of realistically modelling the radial and axial components. Gillmeier et al. (2018) compared vortex models with physically modelled flow fields and showed that Baker and Sterling's model is currently the most realistic on those cited above.

- 85 Debris flight models have also been developed, although they were originally simplified and only considered the drag forces (McDonald et al., 1974) or the drag and lift forces (Lee, 1974). 86 Subsequently, effort has been made to understand the forces involved during the flight of 87 debris. As a result, Twisdale et al. (1979) performed an analysis of tornado missile transport 88 89 using a 'random orientation 6-degree of freedom' 3D model including drag, lift and side forces; Tachikawa (1983, 1988) looked at the flight of flat plates in a wind-tunnel, resulting in the 90 definition of the Tachikawa number (Holmes et al., 2006) and accounting for the ratio of 91 92 aerodynamic to gravity forces; Holmes (2004) and Holmes et al. (2006) developed debris flight 93 equations for spherical and plate-type debris, respectively; Kordi and Kopp (2011) investigated 94 the flight of windborne plate debris from a building in a wind-tunnel; Baker (2007) developed 95 debris flight equations with a dimensionless approach. In a further paper, Baker and Sterling
- 96 (2017) developed the debris flight equations for tornado-like wind field applications.
- 97 Although great effort has been undertaken over the past few decades to model and understand 98 the flow field of a tornado, the flight of debris in a tornado flow field is still poorly understood. 99 It is therefore not surprising that only a little can be found in the literature focusing on 100 windborne debris flight in a tornado-like vortices (Sassa et al., 2009; Maruyama, 2011; Noda et al., 2013; Baker and Sterling, 2017). The current work presents an introductory overview of 101 102 the experimental investigation of windborne debris flight in tornado-like flow field using a 103 tornado generator and the Particle Tracking Velocimetry (PTV) technique and a methodology 104 to compute debris trajectories using experimental data.
- 105 2 DEBRIS FLIGHT INVESTIGATION

### 106 2.1 Experimental methodology

107 2.1.1 University of Birmingham Tornado-like Vortex Generator

108 The University of Birmingham Tornado-like Vortex Generator (UoB-TVG) is a Ward-type 109 generator used to investigate tornado-like vortices (Figure 2). A description of the generator 110 can be found in Gillmeier et al. (2018) but for the sake of completeness a brief description is 111 given below.

112 The generator consists of three different sections:

- a convergence chamber (1m height x 3.6m diameter) located at the bottom. 30 guide
  vanes equally spaced around the convergence chamber introduce angular momentum,
  and the vane angle (θ) can be set up from 0 degree, i.e. no swirling, to 70 degrees.
- a convection chamber (2m height x 3.1m diameter) sitting on top of the convergence
   chamber.

a trapezoidal duct with 9 identical fans sitting on top on the convection chamber and
 generate the uplift through the updraft hole.

- 120 The updraft hole has a radius ( $r_0$ ) of 0.5m and a honeycomb is placed to reduce secondary 121 vortices from the fans interacting with the generated vortex (Ward, 1972). The fans generate a 122 mean vertical velocity (W) of around 10 m/s at the top of the convection chamber, resulting in 123 a radial Reynolds number ( $Re_r = Wr_0/4\pi v$ ) of 5.4 x 10<sup>4</sup>, with v the kinematic viscosity of air.
- 124 In the current work, the vane angle was set to 50 degrees for a resulting swirl ratio of 0.3. The
- swirl ratio is defined as a measure of the circulation strength relative to the updraft (S =  $tan\theta/2a$ ,
- 126 with a the aspect ratio defined by the ratio of the inflow height h and the updraft radius  $r_0$ ).



Figure 2 Schematic and dimensions of the University of Birmingham Tornado-like Vortex Generator (UoB-TVG).

#### 127 2.1.2 Wind velocity measurements

128 The velocity flow field was measured using a TFI 4-hole Cobra probe (TFI, 2011). The Cobra 129 can measure velocity data with magnitude higher than 2 m/s within a cone of influence of 45°. 130 The probe was mounted on a two-axis traverse system located off-centre inside the generator 131 and was held approximatively 0.7m away from the traverse system to minimalize disturbances. Point measurements were undertaken radially every 0.02m from the centre of the generator up 132 to 0.5m and then every 0.04m up to 0.7m; and vertically every 0.02cm from 0.005m to 0.065m 133 134 and then every 0.04m up to 0.425m. The point measurements were taken with a precision of 135 less than 1mm. The velocity data were measured and averaged over a sampling duration of 82s 136 and uncertainties are taken to be  $\pm 0.5$  m/s for the tangential velocity and  $\pm 0.2$  m/s for the radial 137 and vertical velocity (Gillmeier et al., 2018).

#### 138 2.1.3 3D Particle Tracking Velocimetry

139 A full description of the 3D-PTV technique and development can be found in the literature (Maas et al., 1993; Malik et al., 1993). In the current work, the 3D-PTV system consists of 140 141 three digital high-speed cameras, Sony NEX-FS700RH, used to record the motion of the 142 compact debris. Two cameras are positioned at the top of the convection chamber and one camera at the top of the convergence chamber. The cameras were set up to record videos at 480 143 144 Hz at a resolution of  $1920 \times 1080$  pixels. Four 50W LED lights were placed inside the chambers 145 to illuminate the volume of interest. The cameras were synchronised using an ALE718 Multi Camera LANC controller, developed by Applied Logic Engineering, Inc. The cameras 146 147 calibration is performed using a two-dimensional calibration target placed inside the UoB-148 TVG. A three-dimensional target was 3D printed and used to estimate the spatial uncertainties. 149 The resulting root mean square errors in the x, y and z directions are 1.05mm, 1.20mm and 2.15 mm, respectively. The measurement volume in the x, y and z directions is approximately 150 151 is  $2 \times 1.2 \times 0.3$  m, respectively. The digital images were pre-processed by substituting a mask 152 from the images to filter background noises and to enhance the debris visibility. The data 153 reduction was then performed using the open-source particle tracking software OpenPTV 154 (OpenPTV, 2012). The output data were subsequently post-processed using MATLAB®.

#### 155 2.1.4 *Compact debris and cubic model*

156 Spherical Styrofoam beads were used as compact debris in the current work. A particle size 157 and shape analysis using ImageJ software was undertaken to characterise the distributions for 158 a large set of sieved beads (around 3000 samples). The bead diameters were found to be 159 between 1.6mm and 2.3mm, with a mean diameter of  $1.94 \pm 0.1$ mm and a circularity around 160 0.93.

In order to inject the debris inside the simulator, a seeding system was designed and built (Figure 3). It consists of a disc with 100 equidistant holes of 0.002m diameter connected to a stepper motor. The disc is enclosed into a chamber and rotates at a constant speed using a motor. A vent passing through the seeding system and aligned with the holes on the wheel allowed to inject 2mm Styrofoam beads into the simulator. The pressure difference between inside and under the simulator naturally sucked the spheres through the vent. The seeding



Figure 3 Seeding system used to inject debris into the simulator.

- 167 system was attached to the floor under the simulator and the vent was connected to the surface 168 pressure taps. This allowed, as the motor rotates, to inject each individual particle at a time.
- 169 A low-rise building model (20mm sides length x 20mm height, Figure 4) was 3D printed and
- 170 used to initiate debris flight from the building's roof. The building model has a geometric scale
- 171 of 1/8 with regards to the size of the experimental core radius. Wurman et al. (2013) measured
- 172 winds using a Doppler on Wheel radar during an F2 tornado and were able to determine the
- 173 size of the tornado and debris cloud around it. The tornado was found to have a core radius of
- 174 100m with a debris cloud twice as large as the tornado core itself. Therefore, the building model
- 175 would be equivalent to a building of around  $13 \times 13 \times 13m$  at full-scale. In the current work,
- the building model is located at the core radius location and one hundred spheres (compact
- 177 debris) were injected into the flow field from the top of it.



Figure 4 Building model and Cobra probe located at the core radius position.  $V_{\theta}$ ,  $V_{R}$  and  $V_{W}$  denote the wind tangential, radial, and vertical component, respectively, and **V** the wind velocity magnitude.

178 2.2 Numerical methodology

179 The 3D motion of Styrofoam beads in a tornado-like vortex was computed numerically to

180 determine 3D trajectories, following a similar approach from Sassa et al. (2009). A compact

- 181 debris with only drag forces acting and no rotation is assumed. The accelerations of the compact
- 182 debris are defined as:

$$\frac{dV_{\theta,d}}{dt} = k \mathbf{V} \left( V_{\theta} - V_{\theta,d} \right)$$
(1)

$$\frac{dV_{R,d}}{dt} = k \mathbf{V} \left( V_R - V_{R,d} \right) \tag{2}$$

$$\frac{dV_{W,d}}{dt} = k \mathbf{V} \left( V_W - V_{W,d} \right) - g \tag{3}$$

183 where  $V_{\theta}$  and  $V_{\theta,d}$  are the local tangential wind and debris velocities respectively, k is a 184 buoyancy parameter (Eq. 5), t represents the time,  $V_R$  and  $V_{R,d}$  are the local radial wind and 185 debris velocities respectively,  $V_W$  and  $V_{W,d}$  are the local vertical wind and debris velocities 186 respectively, and **V** is the vector of the relative velocity between the wind and debris defined 187 as:

$$\mathbf{V} = \sqrt{\left(V_{\theta} - V_{\theta,d}\right)^{2} + \left(V_{R} - V_{R,d}\right)^{2} + \left(V_{W} - V_{W,d}\right)^{2}}$$
(4)

#### 188 The buoyancy parameter (Holmes, 2004) is defined as:

$$k = \frac{\rho_{air} C_D}{2 \rho_{debris} l} \tag{5}$$

189 where  $\rho_{air}$  is the air density,  $C_D$  the drag coefficient,  $\rho_{debris}$  the debris density and *l* the debris 190 characteristic length. The parameters were set to  $\rho_{air} = 1.2 \text{ kg/m}^3$ ,  $C_D = 0.5$ ,  $\rho_{debris} = 24 \text{ kg/m}^3$ 191 and  $l = 2 \text{ d}_{debris}/3$ , with d the debris diameter, giving a value of k = 9.5.

192 The velocity and position components, denoted hereafter with •, were computed numerically193 using a linear method as:

$$V_{\bullet}^{t+1} = V_{\bullet}^{t} + A_{\bullet}^{t} \Delta t \tag{6}$$

$$X_{\bullet}^{t+1} = X_{\bullet}^{t} + V_{\bullet}^{t} \Delta t \tag{7}$$

194 with  $\Delta t$  a timestep of 0.001s. A timestep of 0.001s offers a good ratio of stability/time efficiency 195 considering the maximal wind velocities of the flow field used in the current work.

196 Experimental data were incorporated into the calculations, by incorporating the experimental 197 wind and tracked data into the calculated accelerations (Eq. 1-4). For t=0, the initial conditions  $(V_{\bullet}^{0} \text{ and } X_{\bullet}^{0})$  were set to the velocity and position data obtained from the particle tracking 198 199 experiment (Eq. 6-7). To determine at each timestep the wind velocities to be incorporated into 200 the calculations, bilinear interpolation was used to interpolate sub-grid velocities from the positions  $X_{\bullet}^{t}$ . Since the measurement grid was coarse, this technique improves the accuracy and 201 202 robustness of the calculations by interpolating wind velocities rather than finding the closest 203 measured point. The modelling of the debris trajectory was stopped when the debris first 204 impacts the ground.

#### 205 3 RESULTS

207

#### 206 3.1 Tornado wind field

Figure 5 shows the 3D velocity flow field and radial profile of the velocity components at the 208 209 lowest height measured ( $z/r_c = 0.03$ ) in the UoB-TVG for a swirl ratio of 0.3. Heights and radial positions are normalised by the core radius  $r_c$ , located at  $r/r_c = 1$ , and velocities are normalised 210 by the maximal tangential velocity  $V_{\theta,max}$ . The core radius was estimated as the radius where 211 212 the maximal tangential velocity occurs and was found to be equal to 0.144m. Figure 5 (a) shows 213 the complexity of a tornado-like flow field, with a strong inflow in the lower level towards the 214 vortex core region and a strong updraft at the corner region  $(r/r_c = 1)$ . The strong tangential velocity region located at the core radius region, the core radius increase with height, as well 215 216 as the positive radial inflow inside the vortex core are consistent with previous work undertaken 217 by Haan et al. (2008), Gillmeier et al. (2018) and Tang et al. (2018). The recirculation located at  $z/r_c = 1$  and  $r/r_c = 2$  seems to indicate the presence of a vortex breakdown, which would 218 219 indicate that for S=0.3 the tornado flow field is not yet fully developed into a two-cell vortex. 220 Vortex wandering characterisation (not shown here) revealed that for the current swirl ratio,



**Figure 5** (a) 3D velocity field for S=0.3. Contour denotes the tangential velocity and the vectors denote the velocity vector between radial and vertical velocity. (b) Velocity components for the lowest height (5mm), located in the boundary-layer.

the vortex typically wanders around the centre of the simulator up to  $0.15r_c$ . Overall, the vortex

- structure shows a relatively good agreement with previous work from Gillmeier et al. (2018)
- and the VorTECH generator for a similar swirl ratio (Tang *et al.*, 2018). Figure 5 (b) shows the tangential, radial and vertical velocity profiles for the lowest height measured and accounts for
- 225 a tangential velocity increasing until the core radius  $r_c$ , a strong radial inflow up (negative radial
- velocities) to half the maximum tangential velocity ( $V_R/V_{\theta,max} = 0.44$ ) at r/r<sub>c</sub> = 2 and a weak
- 227 updraft around the core radius location.

228 Figure 6 shows the vertical profiles of velocities closed to the ground at the core radius location 229 with and without building model included. To measure the vertical profile on top of the model, 230 the Cobra probe's head was mounted under the simulator at the core radius location. The 231 probe's head was placed perpendicular to core centre's direction and at the building model's 232 corner between the top and leeward side, as shown in Figure 4. With no building model, the 233 tangential velocity (Figure 6 (a)) at this location is similar in many respects to a typical 234 boundary-layer profile. The radial velocity (Figure 6 (b)) is predominantly negative over the height and accounts for the radial inflow as found in Figure 5. The vertical velocity (Figure 6 235 236 (c)) shows a change of sign at around  $z/r_c = 0.05$  which is difficult to interpret since the velocity 237 remains relatively close to zero and the measurement is taken in a turbulent region. When the 238 building model was included, the profile was measured from the top of the leeward side, to be 239 as close as possible from the debris release position. It shows that the tangential velocity is 240 typically not affected with height by the building model (Figure 6 (a)), and that the radial and vertical velocities are reduced in magnitude but still display a similar profile with height 241



Figure 6 Vertical velocity profiles of normalised – (a) tangential, (b) radial, (c) vertical velocity, respectively, (d) yaw angle and (e) pitch angle. The black line denotes when the building model is not included into the flow field, and the grey line when it is included. The horizontal capped lines denote the measurement uncertainties. The yaw angle denotes the horizontal angle between the tangential and radial velocities and the pitch angle the vertical angle with regard to the horizontal plane.

(Figure 6 (b and c)). The largest discrepancies observed around  $z/r_c = 0.15$  are associated with 242

a potential flow separation occurring on top the building model. Numerical simulations of a 243 244 low-rise building in tornado-like flow field with a similar swirl ratio (S=0.4) showed that a 245 recirculation is generated on the lee-ward side of the building (Nasir, 2017). That recirculation produces a downward flow in the wake of the building which most likely explain the debris 246 247 behaviour described in the following section. The yaw angle (Figure 6 (d)) refers to the 248 horizontal wind direction facing the probe while the pitch angle (Figure 6 (e)) refers to the 249 vertical wind direction.

#### 3.2 *Example of 3D trajectories from a low-rise building* 250

251 Figure 7 illustrates an example of 3D debris trajectories initiated from the top of a low-rise building located at the core radius location and obtained using 3D-PTV. It shows that the debris 252 253 are initiated with different horizontal and vertical directions resulting in a large spread of the 254 falling locations. Further interpretation and analysis are discussed in the following section.



Figure 7 3D representation of the flight of debris from a low-rise building at the core radius (r<sub>c</sub>) location. The dash line denotes the size the core radius, the arrows denotes the idealised flow-field at building height.

255 3.3 *Comparison of debris flight trajectories with no building and a building included* 256 The comparison between different debris flight configurations is shown in Figure 8. The debris trajectories obtained experimentally are shown in Figure 8 (a and c), while Figure 8 (b and d) 257 show the numerical reproduction of these trajectories. In both cases, visual similarities are 258 259 observed and are quantified in Figure 10. Figure 8 (a and c) illustrate the typical set of experimental data obtained using 3D-PTV when injecting 100 particles from the core radius 260 position. Similar trajectory behaviours were found in the literature, although studied 261 262 numerically, when debris were released from the core radius location (Maruyama, 2011; Noda et al., 2013). In the present cases, the debris were injected from the floor simulating the 263 264 initiation of debris flight in a landscape environment (i.e. no building), and from the top of a 265 building. The tracking was stopped when the particles impacted the ground after being airborne 266 to reflect what could be observed during a full-scale event. However, it is worth noting that due to the elasticity of the Styrofoam bead, its light mass and the smooth floor surface in the 267 268 tornado generator, the beads bounce when falling to the ground. For the sake of the current 269 analysis, such motion has been neglected and is not considered further.

Figure 8 (a) shows that the particles are ejected outward from the vortex following a relatively straight line for a short period of time. The particles are then swirling back again around the vortex before falling to the ground. It also illustrates that a slight variation of the early stage trajectories can result in a large variation of the impact location. The variability in the early stage trajectories observed in the trajectories could be due to the varying size of the beads, although it is most likely that the variation is due to the vortex wandering and/or to turbulent fluctuations of the local wind field. Figure 8 (c) shows the debris trajectories when injected



**Figure 8** Top view of experimental and numerical debris trajectories. Left column denotes the experimental trajectories (a-c), right column the computed trajectories (b-d). The top row denotes the trajectories when the building model is not included (a-b), the bottom row the trajectories when the building model is included (c-d).

277 from the top of the cubic model. It illustrates a greater variation of the early stage trajectories 278 than without the model resulting in a larger region where the debris falls. The larger variation 279 can be attributed to the disturbance of the local flow field around the building model. This 280 assumption can be supported by the initial velocity distributions, i.e. the first debris velocities 281 calculated using 3D-PTV (Figure 9). It appears that debris are driven by positive tangential velocities in both situations (Figure 9 (a)), however radial and vertical velocities have opposite 282 283 sign between the two. As a result, an overall difference of 40 degrees in direction can be noticed 284 when including the building into the flow field (Figure 9 (d)). Furthermore, Figure 9 (c) shows 285 that debris are mainly driven by both positive and negative vertical velocities when released 286 from the top of the building, which could be explained by a potential flow separation. When 287 debris are driven by negative vertical velocity, the debris falls quickly to the ground and is 288 travelling longer distances due to strong local tangential velocities, and therefore accounts for 289 the closest trajectories to the vortex core. On the other hand, the debris tends to be ejected 290 outward the core and to fall at even longer distances away from the core radius. This behaviour 291 is visually observed in Figure 7. Therefore, the risks with windborne debris initiated from a 292 low-rise building are not only associated with long-range falling debris but also with possible 293 short-range impacts at higher velocities.

Figure 8 (b and d) presents the computed debris trajectories using experimental wind and tracking data. In both cases, the computed trajectories are in good agreement with the tracked trajectories. Although the flow field is assumed axisymmetric and does not include any turbulence, it shows that the present methodology can reproduce the trajectories variability. Table 1 compares the components of wind and initial debris velocities and shows that when the building is not included, the velocity components are matching wind and debris. This validates the assumption that variability in debris flight is mainly a wind-driven process. When



**Figure 9** Distribution of debris initial tangential (a), radial (b), vertical (c) velocities, yaw (d) and pitch (e) angle, when the low-rise building model is and is not included in the tornado-like flow field.

- 301 the building is included, large discrepancies are observed between wind and debris which could
- 302 be explained by the fact that velocities are not measured exactly at the same position.

		$\boldsymbol{u}_{\theta} \: / \: \boldsymbol{V}_{\!\boldsymbol{\theta}, max}$	$u_{R}^{}$ / $V_{\theta,max}^{}$	$u_{_W}$ / $V_{_{\theta,max}}$	Pitch (°)	Yaw (°)
No building	Wind	0.30	-0.20	0.04	25.8	4.10
	Debris	0.27	-0.16	0.04	30.7	7.10
Building	Wind	0.70	-0.44	0.27	-32.1	17.7
	Debris	0.38	0.11	-0.09	-16.7	-17.3

**Table 1** Comparison between wind and initial debris velocities, pitch and yaw angles, when the building model was included and not included in the simulations.

303

304 Figure 10 shows the debris flight analysis with normalised flight parameters determined from the debris trajectories (Figure 8). The flight distance (Figure 10 (a)) accounts for the cumulative 305 distance travelled by a debris, the flight time (Figure 10 (b)) the duration while the debris is 306 airborne, V<sub>max</sub> (Figure 10 (c)) the maximal velocity reached by the debris, and flight time to 307 V<sub>max</sub> (Figure 10 (d)) the duration taken by a debris to reach the maximal velocity. Overall, it 308 shows that including a building model does not affect the flight behaviour of the debris 309 310 significantly. This corroborates the assumption that the overall flow field is not affected by the 311 building model, as shown in Figure 6. The numerical simulations tend to reproduce some 312 behaviour, although more variability is generally observed. The flight distance shows good 313 agreement with experimental results and coincides with the debris trajectories overall 314 behaviour (Figure 8), as does the flight time. However, the numerical simulations show 315 limitations in modelling the maximum velocity V<sub>max</sub>, and therefore the flight time to reach V<sub>max</sub> 316 (Figure 10 (c and d)). This could be explained by the flow field variability (due to wandering 317 and/or turbulence) that is diminished after averaging and could result in a stronger 318 instantaneous flow field at the time of the experiment.

	Flight distance/ $r_c$	Flight time* $V_{\theta,\max}/r_c$	$\mathbf{V}_{ ext{max}}/V_{ heta, ext{max}}$	Flight time at $V_{max} * V_{\theta, \max} / r_e$
	0 2 4 6 8 10	2 0 10 20 30	40 0.4 0.5 0.6 0.7 0	0.8 0 2 4 6 8
Exp No building		(b)		
Comp No building			- HH	· · · · · · · ·
Exp Building	· +			· +
Comp Building		· ⊢ − <u>+</u> − − ·		

**Figure 10** Debris flight analysis – the red cross denotes the mean value, the box interquartile range, the vertical line the median and the whiskers the range from minimal to maximal values.

319

#### 320 4 CONCLUDING REMARKS

321 In this work, physical and numerical simulations were used to investigate the flight of debris 322 in tornado-like vortices initiated with and without a low-rise building model. A medium-range 323 vortex was simulated in a tornado-like vortex generator with a swirl ratio of 0.3. Wind 324 measurements displayed a complex flow field with a strong tangential velocity in the corner 325 region of the vortex, and strong radial inflow outside the vortex core. Vertical profiles of winds 326 show that overall, the time-averaged flow field is not significantly affected by included a low-327 rise building model but tends to reduce in magnitude of the radial and vertical velocities with 328 height. The current study focused on releasing Styrofoam beads in a tornado-like flow field 329 and investigates the effect of releasing the debris from the top of the building model. Debris 330 trajectories with and without the building model included show differences in early stage 331 trajectory behaviors. When the building model is not included, trajectories follow a narrower path in early-stage flight with respect to the mean local flow field direction. When the building 332 333 model is included, the early-stage debris trajectories have a different main direction with more 334 variability resulting in a wider falling region. However, the analysis of different characteristic 335 flight parameters shows good agreement between the two situations. It confirms that in the 336 present case the overall flow field in a tornado-like vortex is not affected by including a 337 building model; however, the local flow field in the proximity of the model is affected. 338 Numerical calculations were used to simulate the debris trajectories and flight behaviour. Using 339 debris flight equations with wind and tracked experimental data, the computed trajectories 340 show strong similarities with experimental trajectories. The debris flight analysis shows that 341 the simulations could reproduce the overall trajectories but had limitations in simulating maximum velocities. The limitations could be attributed to the experimental wind data used to 342 343 compute the trajectories and not necessarily to the methodology itself. Finally, this numerical 344 methodology presents advantages to investigate debris flight in tornadoes:

- Gillmeier et al. (2018) showed that analytical vortex models can reproduce some of the behaviours observed in full scale and modelled tornadoes but fail to reproduce the complexity of the 3D flow field. Wind measurements help describing the complexity that models fail to reproduce and therefore integrate a more "realistic" flow field to the study of debris flight.
- Using bilinear interpolation to better approximate the local wind field increases the accuracy of the computed positions and velocities and does not require a fine measurement grid. It also significantly reduces the computation time and does not require high computational power.
- The methodology also allows any type of debris in tornado-like flow field to be studied.
   By adjusting the debris flight equations to either compact (Holmes, 2004) or plate
   (Holmes *et al.*, 2006), a large range of debris type, size and density (i.e. Tachikawa
   number) could be investigated.
- The methodology could also be applied to full-scale tornado wind data, however,
   Doppler radars often fail to measure wind below 30m AGL (Wurman *et al.*, 2013),
   which is where most of debris are becoming airborne and impacting structures. When
   data becomes available, comparison and validation could be undertaken at full-scale.

Although the methodology has many advantages, it also has limitations. The assumption of an axisymmetric flow field does not reflect the complexity of a tornado-like flow field. Volumetric wind measurements using neutral buoyancy tracers and laser illumination (Tomographic PIV, 3D-PTV, etc.) could help retrieving instantaneous 3D flow field. Finally, the methodology only considers averaged flow fields. Turbulence could be incorporated into the simulation (Holmes, 2004) to recreate wind field fluctuations but would require a better understanding of the turbulence in tornadoes/tornado-like vortices.

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#### 374 6 REFERENCES

- 375 Alexander, C. R. and Wurman, J. (2008) 'Updated mobile radar climatology of supercell
- 376 tornado structures and dynamics', in 24th Conf. on Severe Local Storms, Savannah, GA, Amer.
- 377 *Meteor. Soc.*, p. 19.4.
- Baker, C. J. (2007) 'The debris flight equations', *Journal of Wind Engineering and Industrial Aerodynamics*, 95(5), pp. 329–353. doi: 10.1016/j.jweia.2006.08.001.
- Baker, C. J. and Sterling, M. (2017) 'Modelling wind fields and debris flight in tornadoes', *Journal of Wind Engineering and Industrial Aerodynamics*, 168(February), pp. 312–321. doi:
  10.1016/j.jweia.2017.06.017.
- Baker, C. and Sterling, M. (2019) 'Are Tornado Vortex Generators fit for purpose?', *Journal of Wind Engineering and Industrial Aerodynamics*, 190, pp. 287–292. doi:
  https://doi.org/10.1016/j.jweia.2019.05.011.
- Bluestein, H. B. and Unruh, W. P. (1989) 'Observations of the Wind Field in Tornadoes,
  Funnel Clouds, and Wall Clouds with a Portable Doppler Radar', *Bulletin of the American Meteorological Society*. American Meteorological Society, 70(12), pp. 1514–1525. doi:
  10.1175/1520-0477(1989)070<1514:OOTWFI>2.0.CO;2.
- Brooks, H. E. and Doswell, C. A. (2001) 'Normalized Damage from Major Tornadoes in the
  United States: 1890–1999', *Weather and Forecasting*. American Meteorological Society,
  16(1), pp. 168–176. doi: 10.1175/1520-0434(2001)016<0168:NDFMTI>2.0.CO;2.
- Burgers, J. M. (1948) 'A Mathematical Model Illustrating the Theory of Turbulence', in Von
  Mises, R. and Von Kármán, T. B. T.-A. in A. M. (eds). Elsevier, pp. 171–199. doi:
  https://doi.org/10.1016/S0065-2156(08)70100-5.
- Church, C. R. and Snow, J. T. (1985) 'Measurements of Axial Pressures in Tornado-like
  Vortices', *Journal of the Atmospheric Sciences*, 42(6), pp. 576–582. doi: 10.1175/15200469(1985)042<0576:MOAPIT>2.0.CO;2.
- Church, C. R., Snow, J. T. and Agee, E. M. (1977) 'Tornado Vortex Simulation at Purdue
  University', *Bulletin of the American Meteorological Society*. American Meteorological
  Society, 58(9), pp. 900–909. doi: 10.1175/1520-0477(1977)058<0900:TVSAPU>2.0.CO;2.
- Gillmeier, S. *et al.* (2018) 'A reflection on analytical tornado-like vortex flow field models', *Journal of Wind Engineering and Industrial Aerodynamics*, 174, pp. 10–27. doi:
  https://doi.org/10.1016/j.jweia.2017.12.017.
- Haan, F. L., Sarkar, P. P. and Gallus, W. A. (2008) 'Design, construction and performance of
  a large tornado simulator for wind engineering applications', 30, pp. 1146–1159. doi:
  10.1016/j.engstruct.2007.07.010.
- Holmes, J. D. (2004) 'Trajectories of spheres in strong winds with application to wind-borne
  debris', *Journal of Wind Engineering and Industrial Aerodynamics*, 92(1), pp. 9–22. doi:
  https://doi.org/10.1016/j.jweia.2003.09.031.
- 411 Holmes, J. D., Baker, C. J. and Tamura, Y. (2006) 'Tachikawa number: A proposal', *Journal*
- 412 *of Wind Engineering and Industrial Aerodynamics*, 94(1), pp. 41–47. doi: 413 https://doi.org/10.1016/j.jweia.2005.10.004.
- 414 Kakimpa, B., Hargreaves, D. M. and Owen, J. S. (2012) 'An investigation of plate-type 415 windborne debris flight using coupled CFD–RBD models. Part I: Model development and

- validation', *Journal of Wind Engineering and Industrial Aerodynamics*, 111, pp. 95–103. doi:
  https://doi.org/10.1016/j.jweia.2012.07.008.
- 418 Kordi, B. and Kopp, G. A. (2011) 'Effects of initial conditions on the flight of windborne plate
- debris', *Journal of Wind Engineering and Industrial Aerodynamics*, 99(5), pp. 601–614. doi:
  https://doi.org/10.1016/j.jweia.2011.02.009.
- Kosiba, K. A. and Wurman, J. (2013) 'The Three-Dimensional Structure and Evolution of a
  Tornado Boundary Layer', *Weather and Forecasting*. American Meteorological Society,
  28(6), pp. 1552–1561. doi: 10.1175/WAF-D-13-00070.1.
- Lee, A. J. H. (1974) 'A general study of tornado-generated missiles', *Nuclear Engineering and Design*, 30(3), pp. 418–433. doi: https://doi.org/10.1016/0029-5493(74)90227-1.
- 426 Maas, H. G., Gruen, A. and Papantoniou, D. (1993) 'Particle tracking velocimetry in three-427 dimensional flows', *Experiments in Fluids*, 15(2), pp. 133–146. doi: 10.1007/BF00190953.
- 428 Malik, N. A., Dracos, T. and Papantoniou, D. A. (1993) 'Particle tracking velocimetry in three-429 dimensional flows', *Experiments in Fluids*, 15(4), pp. 279–294. doi: 10.1007/BF00223406.
- 430 Maruyama, T. (2011) 'Simulation of flying debris using a numerically generated tornado-like
- 431 vortex', Journal of Wind Engineering and Industrial Aerodynamics, 99(4), pp. 249–256. doi:
- 432 https://doi.org/10.1016/j.jweia.2011.01.016.
- McDonald, J. R., Mehta, K. C. and Minor, J. E. (1974) 'Tornado-resistant design of nuclear
  power-plant structures', *Nucl Safety*. United States, 15(4), pp. 432–439.
- Mishra, Amit R, James, D. L. and Letchford, C. W. (2008) 'Physical simulation of a singlecelled tornado-like vortex , Part A: Flow field characterization', 96, pp. 1243–1257. doi:
  10.1016/j.jweia.2008.02.063.
- Mishra, A R, James, D. L. and Letchford, C. W. (2008) 'Physical simulation of a single-celled
  tornado-like vortex , Part B: Wind loading on a cubical model', 96, pp. 1258–1273. doi:
  10.1016/j.jweia.2008.02.027.
- Mulder, K. J. and Schultz, D. M. (2015) 'Climatology, Storm Morphologies, and Environments
  of Tornadoes in the British Isles: 1980–2012', *Monthly Weather Review*. American
  Meteorological Society, 143(6), pp. 2224–2240. doi: 10.1175/MWR-D-14-00299.1.
- 444 Nasir, Z. (2017) Numerical modeling of tornado-like vortex and its interaction with bluff445 bodies. The University of Western Ontario.
- 446 Noda, M. *et al.* (2013) 'Behavior of Flying Debris in Tornado-like Flow', *Journal of Wind*447 *Engineering*, 38(3), pp. 63–73. doi: 10.5359/jwe.38.63.
- 448 OpenPTV (2012) *What is Open source Particle Tracking Velocimetry*. Available at: 449 https://www.openptv.net/.
- 450 Rankine, W. J. M. (1882) A Manual of Applied Physics. 10th edn. Charles Griff and Co.
- 451 Refan, M., Hangan, H. and Wurman, J. (2014) 'Journal of Wind Engineering Reproducing
- 452 tornadoes in laboratory using proper scaling', *Journal of Wind Engineering and Industrial* 453 *Aerodynamics*. Elsevier, 135, pp. 136–148. doi: 10.1016/j.jweia.2014.10.008.
- 454 Rott, N. (1958) 'On the viscous core of a line vortex', *Zeitschrift für angewandte Mathematik*
- 455 *und Physik 9*, pp. 543–553.

- 456 Sassa, K., Takemura, S. and Yamashita, K. (2009) 'The behaviour of windborne debris
  457 accompanied by a traveling', in *7th Asia-Pacific Conference on Wind Engineering, APCWE-*458 *VII Asia-Pacific Conference on Wind Engineering.*
- Sullivan, R. D. (1959) 'A Two-Cell Vortex Solution of the Navier-Stokes Equations', *Journal of the Aerospace Sciences*. American Institute of Aeronautics and Astronautics, 26(11), pp.
  767–768. doi: 10.2514/8.8303.
- Tachikawa, M. (1983) 'Trajectories of flat plates in uniform flow with application to windgenerated missiles', *Journal of Wind Engineering and Industrial Aerodynamics*, 14(1), pp.
  443–453. doi: https://doi.org/10.1016/0167-6105(83)90045-4.
- Tachikawa, M. (1988) 'A method for estimating the distribution range of trajectories of windborne missiles', *Journal of Wind Engineering and Industrial Aerodynamics*, 29(1), pp. 175–
  184. doi: https://doi.org/10.1016/0167-6105(88)90156-0.
- Tang, Z. *et al.* (2018) 'Characteristics of Tornado-Like Vortices Simulated in a Large-Scale
  Ward-Type Simulator', *Boundary-Layer Meteorology*. Springer Netherlands, 166(2), pp. 327–
- 470 350. doi: 10.1007/s10546-017-0305-7.
- 471 TFI (2011) Turbulent Flow Instrumentation Cobra Probe Getting started guide. Technical
   472 report, Turbulent Flow Instrumentation.
- Twisdale, L. A., Dunn, W. L. and Davis, T. L. (1979) 'Tornado missile transport analysis', *Nuclear Engineering and Design*, 51(2), pp. 295–308. doi: https://doi.org/10.1016/00295493(79)90096-7.
- Ward (1972) 'The exploration of certains features of tornado dynamics using a laboratorymodel'.
- Ward, N. B. (1972) 'The Exploration of Certain Features of Tornado Dynamics Using a
  Laboratory Model', *Journal of the Atmospheric Sciences*. American Meteorological Society,
  29(6), pp. 1194–1204. doi: 10.1175/1520-0469(1972)029<1194:TEOCFO>2.0.CO;2.
- Wurman, J. and Alexander, C. R. (2005) 'The 30 May 1998 Spencer, South Dakota, Storm.
  Part II: Comparison of Observed Damage and Radar-Derived Winds in the Tornadoes', *Monthly Weather Review*. American Meteorological Society, 133(1), pp. 97–119. doi:
  10.1175/MWR-2856.1.
- Wurman, J., Kosiba, K. and Robinson, P. (2013) 'In Situ, Doppler Radar, and Video
  Observations of the Interior Structure of a Tornado and the Wind–Damage Relationship', *Bulletin of the American Meteorological Society*. American Meteorological Society, 94(6), pp.
- 488 835–846. doi: 10.1175/BAMS-D-12-00114.1.
- 489