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A simple vortex model of a thunderstorm downburst – A parametric evaluation

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A R T I C L E I N F O

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A B S T R A C T

Thunderstorm downbursts are short-lived, transient extreme wind events which can cause wind speeds equivalent to a category EF3 tornado (~150mph). The complex flow field which they produce has previously been the subject of time-expensive numerical modelling. However, it is well-known that there is a large, random variation in full-scale downbursts and so a quick, easily varied model would be of benefit to engineers calculating dynamic loading on structures. This paper introduces a simple and computationally inexpensive vortex model of a downburst, which is shown to model the main features of the flow field in a physically simulated thunderstorm downburst to an appropriate degree of accuracy.

1. Introduction

A thunderstorm downburst is a transient, highly localised extreme wind event which can cause wind speeds of 150mph, equivalent to a category EF3 tornado (Fujita, 1985). These events are created by the cooling of (and precipitation within) warm, moist, rising air in a convective thunderstorm cell, which then reverses direction to form a downdraft which impinges on the ground. A primary ring vortex forms around the downdraft, and is carried radially outwards with the outflow from the impingement point. The superposition of the outflow and vortex flow fields creates a region of very high wind speed. Numerical simulations also indicate the development of a smaller, secondary vortex at the base of the primary (Kim and Hangan, 2007, Mason et al., 2009), caused by the interaction of the flow and ground roughness. The combination of these flow elements results in a flow field which is very different from that seen in atmospheric boundary layer (ABL) flows. Unlike ABL winds, which for the purposes of design are regarded as statistically stationary over a number of hours and uniform over tens of kilometres, downbursts typically have a lifetime of only a few minutes and a downdraft radius of approximately 1–2 km, with a non-stationary time-series The vertical distribution of radial wind-speed typically has a peak maximum (u_m, the spatio-temporal maximum over the whole flow field) close to the ground, at a height (z_m) of 30–100 m at full-scale. These features are illustrated for the physically simulated downburst which is the subject of this paper in Fig. 1. One feature of downbursts is the variability of such events, with no two recorded downbursts producing precisely the same flow fields (Choi, 2004; Lombardo, 2011; Lombardo et al., 2014), although there are clear similarities between the large-scale characteristics.

There is growing consensus that severe thunderstorm events may become more frequent due to climate change (e.g. Brooks, 2013). Consequently, efforts have been made to understand the wind loading which they exert. Due to the difficulty in predicting where and when a downburst will occur, along with the usual issues of variability, the use of full-scale measurements for the determination of downburst wind loading is problematic (though the work of Lombardo (2011)) provides a very useful data set for validation. For this reason, simulations are used to model downbursts and (in some cases) their effects on structures, both physically (e.g. (Butler and Kareem, 2007; Chay and Letchford, 2002a, 2002b; Jesson et al., 2015a; 2015b; Lundgren et al., 1992)) and numerically (Mason et al., 2009; Orf et al., 2014; Vermeire et al., 2011). The more advanced physical simulators, such as that used by McConville et al. (2009) and Jesson et al. (2015a, 2015b), model the transient nature of a downburst event, and exhibit the same run-to-run variation which has been seen as with full-scale events (McConville et al., 2009). This variation limits the insight which can be gained, although general loading patterns may be quantified (e.g. Jesson et al., 2015a; 2015b). On the numerical side, techniques such as Large Eddy Simulation and cloud models have been used, with the lifecycle of the downburst being simulated from the initial downdraft to the formation and motion of the ring vortex. Although they are of importance in elucidating the mechanisms which drive a downburst and lead to their high wind speeds, these techniques are computational expensive. Holmes and Oliver (2000)

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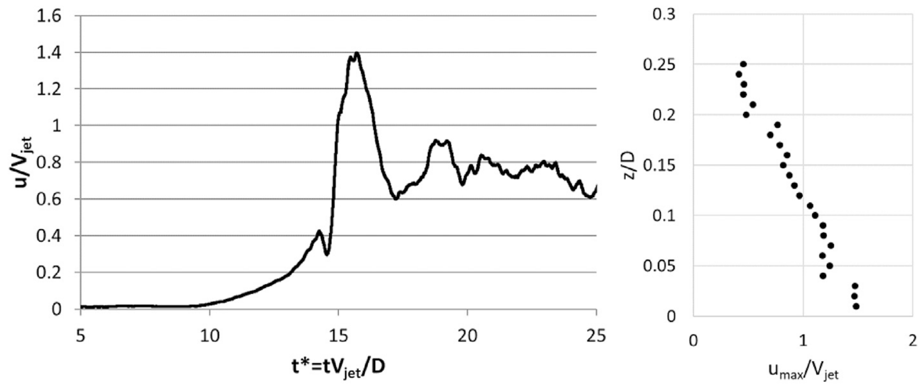

Fig. 1. (left) Wind-speed time-series and (right) vertical profile of temporal maximum wind speeds from a physically simulated downburst.

suggested a simple empirical model, based around a time-varying impinging jet profile. Arguably, this model lacks a clear relationship to the components making up the complex flow field, and therefore does not suitably model vertical variation.

A simple numerical model of a downburst is presented in this paper. This model extends the concepts developed for the purpose of flight simulation by Ivan (1986) and Schultz (1990), who developed potential flow models of stationary, time-invariant downburst flows. Before presenting the model definition, a brief description of the University of Birmingham Transient Wind Simulator (UoB-TWS) is given in Section 2; experimental data from the UoB-TWS provides the reference data for model validation. The model, which is described fully in Section 3, calculates the velocity field as a superposition of a primary vortex, secondary vortex and linear outflow velocity. Section 4 compares model output with the UoB-TWS data, and includes a parametric study which identifies the important parameters in defining and creating a downburst flow field. Finally, important conclusions from this work are presented.

2. University of Birmingham transient wind simulator (UOB-TWS)

The UoB-TWS is a vertical impinging jet downburst simulator with a length scale estimated as 1:1600 and is described fully by Jesson et al. (2015a, 2015b). Aperture control is used to simulate the rapid flow accelerations which occur in full-scale downbursts and the simulator has been shown to simulate the transient aspects of a downburst flow (Jesson et al., 2015a, 2015b; McConville et al., 2009). Run-to-run variation is seen in the simulations, as has been noted in full-scale events and mentioned in the introduction. In order to investigate the generic aspects of downbursts, while minimising the effects of such variation, an ensemble-mean approach has been used in analysing the UoB-TWS data. Thus, time-series from multiple runs are averaged according to:

$$u(t) = \frac{1}{N}\sum_{n=1}^{N} u_n(t) \tag{1}$$

where $u(t)$ is the ensemble-mean velocity time-series, n is the run index, N is the total number of runs in the ensemble and $u_n(t)$ is the velocity time-series from the n^{th} experimental run. Ensemble-mean values are used in this paper.

The aim of the original UoB experiments was to measure the wind loading on building models in a simulated downburst. The velocity measurements had two purposes: Firstly, to identify the position, (x_m, z_m), of the peak maximum outflow velocity (found to be $x_m/D = 1.50$, $z_m/D = 0.02$), where x is the radial distance from the centre of the downdraft, z is the vertical position and D is the diameter of the simulated downdraft and m denotes a maximum, and secondly to ensure that the vertical profile of radial velocity at this point was consistent with full-scale data (which was demonstrated by comparison with the work of Hjelmfelt (1988); see (Jesson et al., 2015b)). Velocity measurements were made at 10 mm vertical spacings for profiles measured at $x/D = 1.00$, 1.50, 2.00 and 2.50, with partial profiles (vertical positions around z_m only) at $x/D = 1.25$ and 1.75 to verify that the $x/D = 1.50$ profile included the maximum velocity point.

3. The vortex model

3.1. Model development

An early version of the vortex model has been presented by Jesson and Sterling (2016) and this description is expanded and updated here. This model uses similar concepts to those applied by Ivan (1986) and Schultz (1990), with the addition of a secondary vortex component and temporal variation. A non-translating downburst is simulated, i.e., the downburst is not part of a larger storm which carries the downburst with it (although incorporating the translation of the storm would be programmatically straightforward as an improved understanding of the movement of a downburst front within the wider storm becomes available). This permits the assumption that the downdraft creates an axially symmetric outflow around the impingement point, meaning that model is 2-D within a cylindrical polar coordinate system; variation occurs along the radial (x) and vertical (z) directions only. The respective velocities are u and w, and the velocity field is assumed to be the superposition of three, independent velocity fields, one from each of the main flow structures:

- The main outflow from the downdraft impingement point.
- The primary ring vortex.
- The secondary vortex.

This superposition is a technique applied in (inviscid) potential flow models, as is the use of mirrored vortices (Fig. 2) to ensure that the condition of zero flow across the ground plane is met. The mirroring of the vortices also accelerates the radial flow close to the boundary, as required by continuity to reflect the contraction of the flow field by the ground plane. The inviscid model also means that there is no "no-slip" condition at the ground plane; however, at present the variation of velocity very close to the ground (i.e., the boundary layer) remains an open point. Thus, vertical velocity profiles and been plotted for the above ground region ($z/D > 0.01$). Radial motion of the vortices is governed purely by the outflow velocity (a model parameter; vertical motion is a separate model parameter, as discussed later). This outflow velocity is modelled as linearly increasing (more details are given in Section 3.2). In standard potential flow theory, the flow is assumed to be inviscid, leading to vortices with a singularity at the centre. In this model, each vortex is an independent (viscous) Rankine-type vortex. For a circular Rankine vortex with a core of radius R and circulation Γ, the tangential wind speed at a radial distance r from the centre, $V_\theta(r)$, is given by: