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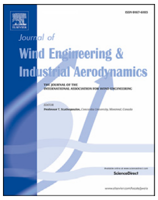

A parametric study of downbursts using a full-scale cooling source model

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ABSTRACT

Large Eddy Simulations (LES) using an idealized cooling source (CS) downburst model have been used to investigate the important geometric and thermal parameters that govern a thunderstorm downburst outflow. These simulations use the Bryan Cloud Model, version 1 (CM1), a meteorological cloud model for atmospheric phenomena. A significant variation in thermodynamic cooling exists in a downburst-producing thunderstorm cloud and this paper presents an assessment of some aspects of that variation. Certain quantities, such as the downburst cooling source shape, size, aspect ratio, height above datum and peak cooling source intensity are modified. An existing scaling procedure has been adopted for a non-dimensional analysis of density-driven downburst wind-related metrics, with some success. The total horizontal area that experiences potentially damaging winds speeds (of Enhanced Fujita scale EF0 and EF1 magnitudes) at $z = 50$ m AGL (the typical height of an electricity transmission tower) and 10 m AGL is proportional to the initial geometric parameters of the CS. Cooling rate modification adds a temporal influence on the EF areas that is not observed in simulations when the cooling rate is kept the same.

1. Introduction

Downbursts are downdrafts of air which descend out of a thunderstorm cloud, impinging upon the ground causing a radial outflow of wind (Fujita, 1985). They are the result of thermodynamic processes in the thunderstorm, such as the formation of rain, snow, hail and other types of precipitation (Fujita, 1985). The formation of precipitation results in thermodynamic cooling, where heat is removed from the entrained air, creating a large body of cooler more dense air within the cloud which descends to the earth's surface due to negative buoyancy. Additionally, the drag which is induced by the falling of this precipitation aids in the evolution and strength of the downburst (Orf et al., 2012). The winds which result from this have enormous potential to damage man-made structures on the ground, such as buildings (Mason, 2009a; Jesson et al., 2015a) and electricity transmission line structures (Kim and Hangan, 2007; Aboshosha and El Damatty, 2015; Aboshosha et al., 2016), and follow a wind speed profile which does not conform to those of the well-defined synoptic winds. The difference from synoptic winds makes designing structures for this type of wind loading a particular challenge. A downburst descends out of the cloud producing a primary roll vortex, due to baroclinically generated vorticity (Bluestein, 2007; Vermeire et al., 2011a), then impinges upon the ground creating a secondary stronger roll vortex along the surface, travelling radially outward. A downburst has characteristically strong radial peak winds, as well as large positive and negative vertical winds within the roll vortex. Peak outflow winds within a downburst profile also occur at elevations much closer to the ground than the typical synoptic wind profile (Fujita, 1985).

Proctor (1988) simulated a downburst by replicating the thermodynamic cooling in the atmosphere using environmental conditions observed during the Joint Airport Weather Studies (JAWS) project (Hjelmfelt, 1986, 1988) and initiated the initial downdraft by specifying precipitation at the top of the domain and allowing it to descend. Early attempts to replicate downburst outflow winds by means of a simplified approach more analogous to modern engineering models used an impinging jet (IJ) model (Selvam and Holmes, 1992). The impulsively driven IJ downburst model seems to originate from Fujita (1985), even though it lacks the realistic physics present in natural events because the primary mechanism driving the jet flow is not negative buoyancy but, rather, an artificial impulse of momentum. Additionally, the steady IJ model does not accurately capture the formation and evolution of the primary roll vortex, as the down flows of natural events are not steady state but transient. Unsteady Reynolds-Averaged Navier-Stokes (URANS) simulations of an IJ found that, although the outflow roll vortex formed,

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it was initiated by a Kelvin-Helmholtz instability at the shearing interface between the nozzle and ambient fluid (Kim and Hangan, 2007), an artifact not observed in natural events. As established in Anderson et al. (1992) and Vermeire et al. (2011a), any numerical model that aims to accurately capture the outflow dynamics of a natural event should take into account the primary driving mechanism of the flow, buoyancy. The cooling source (CS) model, an idealized numerical approach, attempts to replicate the thermodynamic processes in the thunderstorm cloud by introducing a spatially and temporally dependent CS which "grows" within the atmosphere. This approach appears to better replicate the primary means of vorticity generation and, as a result, more accurately replicates the peak outflow wind velocities (magnitude and shape of vertical profiles) (Vermeire et al., 2011a).

The CS model investigated in the present work was first introduced in Anderson et al. (1992), where an elliptical CS, with a cooling rate that varied spatially (as a $\cos^2$ function both horizontally and vertically across the source) and temporally, was placed into a dry adiabatic atmosphere. The imposed thermal forcing functions in that study were originally estimated from ice-phase cloud model simulations (Straka and Anderson, 1993). The physical dimensions of the ellipsoidal CS function were approximated to represent the thermodynamic cooling region within the full cloud model thunderstorm simulation of (Anderson et al., 1992). The more idealized CS sub-cloud model was run using the Wisconsin Model Engine (WME) (Anderson et al., 1992; Orf et al., 1996; Orf and Anderson, 1999) which is a reduced sound speed system (Anderson et al., 1986; Droegemeier and Wilhelmson, 1987) introduced for the parallelization of computationally expensive meteorological simulations. Two adjacent CS, each with a horizontal half width of 1200 m, vertical half width of 1800 m, a peak cooling forcing rate of -0.052 K/s and a vertical height of the centre of the CS of 2000 m was used by Anderson et al. (1992). The cooling ramp-up function consisted of a 2 min cooling rate ramp-up period followed by a 10 min steady state cooling period, and then a 2 min ramp-down period to zero cooling rate. The results from Anderson et al. (1992) were promising as they closely represented the wind fields in the more realistic simulations, whilst the source of the flow was generated in a physically realistic way that matched the thermodynamic cooling present in natural events. It was also found that agreement was reasonable when compared to the axi-symmetric isolated downburst simulation of Proctor (1988). This CS model has since been employed in other studies, for example within the WME to examine in more detail colliding microburst outflows through a parametric study investigating the effect of the spatial separation of two CS (Orf et al., 1996). The effects of horizontal translation of the CS function in a unidirectional sheared environment were also studied (Orf and Anderson, 1999).

The same CS forcing function code was carried over (Lin et al., 2007) to Cloud Model 1 (CM1) (Bryan and Fritsch, 2002), a more sophisticated cloud model specialized for simulations of deep moist convection (DMC) which can easily be modified for more simple sub-cloud model simulations like thunderstorm downburst winds. A modified CS ramp-up function peak value was used in that study (to approximate the higher outflow wind speeds observed in some more intense natural thunderstorm downbursts). It was concluded that an idealized CS model is a practical simplification of the thermodynamic cooling in a natural thunderstorm as the various parameters of the source itself can be modified (Lin et al., 2007). A similar CS model from the WME was used within CM1 (Vermeire et al., 2011a; b). In Vermeire et al. (2011a) the model was compared to an impulsively driven IJ model run within CM1, finding that the IJ model cannot capture the realistic buoyancy driven effects of natural events, concluding that all further study of simplified downburst models should be conducted using the CS approach. A colliding downburst line outflow study using CM1 (Vermeire et al., 2011b) showed that colliding outflows result in wind fields having larger damage footprints and peak outflow velocities greater than those of a single event, notably in the region of the colliding outflows caused by a burst swath. A 70% increase in the area where a surface structure would encounter damage due to the increased surface footprint of a downburst line event, and 55% increase in peak outflow radial wind speeds when compared to an isolated event were observed (Vermeire et al., 2011b). It was also found that the LES approach of CM1 resulted in more reliable data, when compared to the scale adaptive simulation (SAS) URANS simulations of (Mason et al., 2009b). The same CS function presented in Anderson et al. (1992) has also been used in other numerical studies including Anabor et al. (2011), which concluded that the sub-cloud LES CS model is capable of replicating the characteristic length and time scales present in full cloud simulations.

In downburst events there is large spatial variability within the thermodynamic cooling present in the thunderstorm. Cooling rate and the size and shape of the CS are all subject to atmospheric conditions, such as variation in temperature and wind shear. The CS model was investigated in Mason et al. (2009b) by a parametric study that employed a similar CS approach to that of Anderson et al. (1992), but using a commercial software package. Various physical attributes of the CS were modified including the CS diameter, shape, forcing intensity, temporal downdraft characteristics, environmental lapse rate and surface roughness. It was found that the normalized peak outflow velocities were not greatly affected by changing the various parameters of the CS. However it was noted that the relationship between outflow velocities and the downdraft diameter are not linearly related as they are in the IJ model. Notably, the shape of the CS had a significant effect on outflow vortex development and so it was concluded that any future study should carefully consider the shape of the CS. Similar effects were observed for variations in other parameters such as the temporal characteristics of the ramp-up function and the elevation of the CS above ground. Although comprehensive, Mason et al. (2009b, 2010) did not offer a scaling approach for quantifying the effects of the physical changes of the source and their strong temporal dependence. In contrast, a frequently-used scaling method exists for the IJ model which linearly relates peak outflow wind speed and the spatial locations in the wind velocity field to the magnitude of the initial peak velocity and nozzle diameter of the IJ, respectively (Letchford and Chay, 2002; Kim and Hangan, 2007). As noted by Jesson et al. (2015b) other scales may be more appropriate, an example being the outflow vortex diameter as examined by Vermeire et al. (2011a) which showed how such scales were different when comparing IJ and CS simulations. The present study seeks to investigate if a suitable scaling method exists for the CS model, relating the CS size, shape and cooling rate to outflow properties such as peak wind speed. The scaling approach introduced in Lundgren et al. (1992) and Yao and Lundgren (1996) is investigated here. Those authors performed physical downburst model studies that involved the release of dense liquid parcels, into a less dense ambient fluid environment, which then impinged on a smooth horizontal surface. An inviscid scaling law was proposed for comparison between the transient features obtained from multiple experiments. It was found that this scaling law worked fairly well for simplified experiments where the fluid density changes abruptly between the source and ambient environment, as was the case in other liquid release experiments (Alahyari and Longmire, 1994). The present work investigates whether the same scaling laws are applicable to the more spatially-complex CS model, where the density change between the source and the environment is more gradual. The questions addressed are:

1. Does the overall size of the CS have any impact on peak outflow wind velocity magnitudes and their locations (radial and vertical)?
2. What is the effect of modifying the CS peak cooling rate at the geometric centre of the CS?
3. Can a CS type downburst model be scaled in a similar way to the IJ model (i.e. a source diameter and height)?
4. Can the scaling approach in Lundgren et al. (1992) be applied to the spatially and temporally dependent CS model, or is that scaling limited to simplified constant density sources?