A COMPARISON OF IMPINGING JET AND COOLING SOURCE DOWNBURST MODELS

Brian C. Vermeire[1], Leigh G. Orf[2], Eric Savory[3]

[1]University of Western Ontario, 1151 Richmond Street, London, ON, Canada, bvermeir@uwo.ca
[2]Central Michigan University, Mount Pleasant, MI, USA
[3]University of Western Ontario, 1151 Richmond Street, London, ON, Canada

15 September 2009

I. INTRODUCTION

A thunderstorm downburst is defined as an intense downdraft of air that induces an outburst of damaging winds on or near the surface of the earth. The structure, evolution and atmospheric conditions conducive to downburst events have been documented (Fujita 1985), showing that downbursts are caused by liquid water loading and thermodynamic cooling. This produces a dense, cool downdraft of air that descends from the base of a thunderstorm cloud. A leading edge roll vortex is formed due to shear instability with the surrounding air. The downdraft then impinges on the ground and spreads radially at high velocities, propelling the roll vortex in front of the outflow.

Previous studies on downbursts include both a cooling source approach, as taken in Lin et al. (2007), and an impinging jet model after Kim and Hangan (2007). The cooling source model uses a specified cooling function in a dry adiabatic atmospheric model. This cooling function is specified to mimic the effects of melting and sublimation in an actual downburst event, resulting in a physically realistic simulation. The impinging jet model takes advantage of observed similarities in the outflows of downbursts and laboratory scale jets. The advantage of the impinging jet is that it can be simulated in a laboratory setting; however it is limited by physically unrealistic forcing. The objective of the present work is to outline the similarities of these two modelling methods. This is performed by using a novel vortex scaling approach, solving problems associated with the scaling of thunderstorm downbursts.

II. PRESENTATION OF RESEARCH

Both the models are solved using large eddy simulation (LES) with the Bryan Cloud Model (CM1) (Bryan 2002). This model is completely dry, utilizing a Klemp-Wilhelmson time splitting scheme for integration of acoustic waves. A 5th order scheme is used for horizontal and vertical advection. Subgrid turbulence is handled by the k-ε turbulence model. The computational domain for the cooling source simulations extends to 3.5 km in both horizontal directions and 4.0 km vertically. Horizontal grid spacing is constant 10 m, while vertical spacing stretches from 1 m at the surface to 50 m at the top of the domain. For the impinging jet model, a constant horizontal grid spacing of 0.01 jet diameters (D_j) is used, extending to 3.5 D_j. The vertical grid stretches from 0.001 D_j at the surface to 0.07 D_j at the top of the domain. The forcing functions are centred on one vertical edge of the domain for both models and the two mating faces are symmetry boundary conditions. This allows for the simulation of one quarter of a downburst event, as both models are axisymmetric. The other two faces and top of the domain are specified as outflow boundary conditions. The surface is modelled by a drag coefficient, based on the stability affected log law. Nondimensional wind shear is specified according to Hogstrom (1996).

The forcing function for the cooling source models has an ellipsoidal shape identical to that in Lin et al. (2007). The centre experiences the greatest cooling, decreasing in magnitude towards the outer edge. The intensity of the cooling function increases from 0 K/s to a peak of -0.08 K/s during the simulation. The ellipsoid has horizontal and vertical half-widths of 1200 m and 1800 m respectively and is centred at a height of 2000 m. Surface roughness levels of 0.1 m, 0.03m, 0.01 m, 0.003 m and 0.001 m are investigated. The impinging jet simulations are performed at Re = 10^5 with an H_j/D_j ratio of 2.0. These are chosen according to the availability of experimental data and the practical limitations of future experiments. Surface roughness levels of 10^{-4}, 10^{-5} and 10^{-6} D_j are considered.

The scaling approach used in this study is based on a Galilean-invariant frame of reference, fixed to the centre of the roll vortex. This allows for a direct comparison of the simulated outflows, independent of the inlet conditions. This avoids scaling issues as a downburst, unlike an impinging jet, does not have a universal length or velocity scale. The length scales used to compare the two outflows include the horizontal and vertical vortex diameters (D_V and H_V), the height of the vortex centre (C_Y), and the horizontal and vertical locations of the peak velocity (x_{Up} and y_{Up}) as shown in Figure 1. The dimensions x_{Up} and y_{Up} are measured from the surface and the left hand side of the primary vortex respectively.

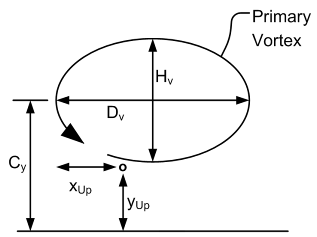

FIG. 1: Length scales used for comparing vortex structures.

This yields four separate nondimensional groups that can be compared, specifically x_{Up}/D, y_{Up}/D, C_Y/D and the aspect ratio of the vortex D_V/H_V. The location of the peak velocity in the domain is readily available, but the determination of the vortex parameters D_V, H_V and C_Y require an objective and frame independent vortex identification method. The method employed is based on the q-surface after Hunt et al. (1988), allowing the extents of the vortex to be defined as any interconnected region with positive q, where:

$$q = \frac{1}{2}\left(u_{i,i}^2 - u_{i,j}u_{j,i}\right)$$

This allows the location of peak velocity to be scaled by the jet diameter as shown in Figure 2, where each point represents a different time in the simulation.

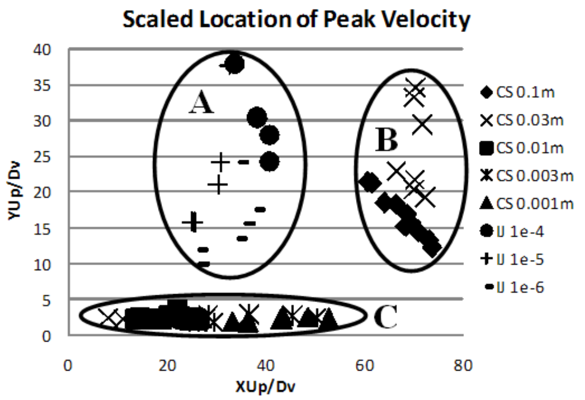

FIG. 2: Scaled locations of peak velocity for impinging jet (IJ) and cooling source (CS) simulations.

It is observed that U_P for the impinging jet simulations occurs in one grouped region A, and in two distinct grouped regions, B and C, for the cooling source simulations. For the impinging jet simulations the horizontal location remains between 20-40 percent of D_j. By decreasing the surface roughness, the point of peak velocity tends to move closer to the surface. For the two roughest cooling source models, the point of peak velocity tends to occur towards the front of the vortex and high above the surface in group B. For the smooth cooling source models, the point of peak velocity is extremely close to the surface, under 5 percent of D_j. It is evident that there is no overlap between regions A and B or regions A and C, suggesting that the model outflows are not similar.

The second comparison that can be made is between the roll vortex aspect ratios for both modelling methods. These are shown in Figure 3 for both sets of simulations.

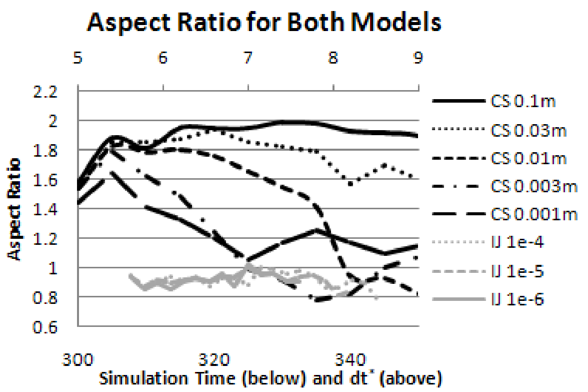

FIG. 3: Aspect ratio both sets of simulations during time of high outflow velocity ($dt^* = tV_j/D_j$ for the impinging jet).

The cooling source aspect ratio is highly sensitive to the level of surface roughness. With the exception of the 0.003 m roughness case, all aspect ratios lie between 1 and 2. The impinging jet simulations are insensitive to the level of surface roughness. All aspect ratios lie between 0.8 and 1, significantly different from the cooling source results.

The final nondimensional group to be compared is the relative height of the roll vortex from the surface. These are shown in Figure 4 for both simulation cases.

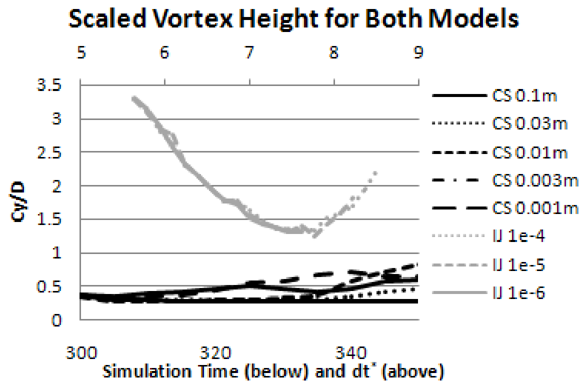

FIG. 4: Scaled vortex height both sets of simulations during times of high outflow velocity ($dt^* = tV_j/D_j$ for the impinging jet).

For the cooling source simulations it is apparent that the vortex centre starts at $C_Y/D = 0.4$ at the beginning of the outflow period. It then varies depending on the level of surface roughness. It is apparent that the impinging jet vortex height is relatively insensitive to the amount of surface roughness. For all cases, the impinging jet vortex centre is higher than that of the cooling source model. Therefore, it cannot be concluded that they produce similar outflow features.

III. RESULTS AND CONCLUSIONS

Both cooling source and impinging jet downburst simulation have been performed. The outflow features from these simulations were scaled based on the extents of the primary roll vortex, resulting in a direct comparison of the outflows. It has been shown that there is no similarity between the location of peak velocity, height of the roll vortex above the surface and vortex aspect ratio. Based on these results it can be concluded that the outflow from an impinging jet of Re 10^5 and $H_j/D_j = 2$ is not similar to that of a realistic downburst event. This suggests that an investigation of the Reynolds number effects on transient impinging jet outflows is necessary.

V. REFERENCES

Fujita T., 1985: The downburst microburst and macroburst. *University of Chicago, Department of Geophysical Sciences,* 128 pp

Lin W., Orf L., Savory E., Novacco C., 2008: Proposed large-scale modelling of the transient features of a downburst. *Wind and Structures, 10* 315– 346

Kim J., Hangan H., 2007: Numerical simulations of impinging jets with application to thunderstorm downbursts. *Journal of Wind Engineering and Industrial Aerodynamics, 95* 279– 298

Bryan G., 2002: An investigation of the convective region of numerically simulated squall lines. PhD Thesis. *The Pennsylvania State University,* 181 pp

Hogstrom U., 1996: Review of some basic characteristics of the atmospheric surface layer. *Boundary Layer Meteorology, 78* 215– 246

Hunt J., Wray A., Moin P., 1988: Eddies, stream and convergence zones in turbulent flows. *Center for Turbulence Research Report, CTR-S88* p. 193