Numerical Simulation And Scaling Of Thunderstorm Downburst Outflows

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A thesis submitted in partial fulfillment of the requirements for the Master of Engineering Science degree in Mechanical and Materials Engineering
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Abstract

A downburst is a natural phenomenon that occurs during thunderstorms, creating hazards and damage to infrastructure due to the strong winds produced. This research contributes to the current literature by applying the Lundgren et al. scaling parameters ($R_0$, $T_0$, $V_0$) to scale cooling source (CS) downburst simulations. The research also investigates the effects of the environmental lapse rate (ELR) on full-scale downburst outflows and compares the full-cloud model with the subcloud model simulations. The results showed that the scaling parameters preserve the temporal and vertical radial wind speed profile shape, as well as the wind speed locations. The primary and the secondary vortices are also preserved. Lower ELR resulted in downbursts with lower peak wind speed. A peak radial wind speed of 52.0 m/s is observed when ELR = 9.80 K/km, which decreases to 39.6 m/s when ELR = 7.76 K/km. Lower ELR also delayed the downdraft evolution, which is reflected in the outflow development. This research also found that the CS model can be employed to simulate the more realistic simulations of downbursts produced by full-cloud models. This aids in simulating realistic downbursts without relying on the expensive full-cloud models.

Keywords

Cloud model, cooling source model, downburst, environmental lapse rate, full-cloud model, scaling parameters, thunderstorm.
Summary for Lay Audience

Downbursts are a natural phenomenon characterized by outward and straight-line strong winds near the ground. A downburst phenomenon can be identified when several trees in a forest are pushed in one direction. A downburst is modelled experimentally using the liquid release method, which consists of releasing a fluid that is slightly denser than the ambient fluid contained in a tank or flume, creating a downdraft that descends to the ground surface. Previous researchers proposed length ($R_0$), time ($T_0$), and velocity ($V_0$) scaling parameters that allowed comparisons of liquid release experiments with real-world events. In addition, these scaling parameters allow comparison with the numerical simulation results. This research implements these parameters to scale numerical model data obtained from a full-scale downburst simulation using a cooling source (CS) model, which is a numerical model used to simulate downbursts. The resulting scaled velocity profiles are similar to the scaled profiles observed in full-scale downburst measurements and preserve the vertical location of the near-ground peak wind speed, which is of great interest to the wind and the structural engineers. The research also examines the effects of environmental conditions on downburst events. The results showed that downbursts are affected by the temperature lapse rate of the ambient, which is defined as the decrease of temperature with altitude. Weak wind speeds are produced when the temperature lapse rate is less than 9.80 K/km. However, the structure of the downflow and the radial outflow does not change as long as the downdraft intensity is high enough so that it reaches the surface before losing its driving force. Finally, the thesis investigates the use of the CS model to replicate downburst events produced by the more realistic numerical models that simulate thunderstorm clouds (full-cloud models). This lays the groundwork for the use of CS models to simulate more realistic downburst events without relying on the expensive full-cloud model simulations.
Co-Authorship Statement

This thesis is prepared in accordance with the specifications of the integrated-article format by the School of Graduate and Postdoctoral Studies (SGPS) at the University of Western Ontario. Each article's co-authors and contributions are listed below:

**Chapter 3: Implementation of the Lundgren et al. (1992) scaling parameters for full-scale cooling source model.**

The simulations were carried out by Cristiano Kondo, whilst Professor Eric Savory provided some data. The literature review, post-processing, discussion, and drafting of the manuscript were carried out by Cristiano Kondo with the assistance and suggestions of Professor Eric Savory.

**Chapter 4: Simulation of downburst outflows with different ambient conditions using full-scale cooling source model.**

The simulations were carried out by Cristiano Kondo under the supervision of Professor Eric Savory and the assistance of Dr. Leigh Orf of Wisconsin University to set up the latest version of Cloud Model 1 (CM1). Cristiano Kondo conducted the literature review, post-processing, and manuscript drafting with the assistance and suggestions of Professor Eric Savory.

**Chapter 5: Investigation of a cooling source template that produces downburst outflows similar to those produced by full-storm cloud models.**

The simulations were carried out by Cristiano Kondo with the guidance of Professor Eric Savory, and Dr. Leigh Orf provided the atmospheric sounding data for the simulations. The literature review, post-processing, discussion, and drafting of the manuscript were carried out by Cristiano Kondo with the assistance and suggestions of Professor Eric Savory.
Acknowledgments

I would like to express my gratitude to my supervisor, Professor Eric Savory, for his guidance and immense support throughout this research. His feedback, suggestions, and orientation aided in the completion of this thesis.

I would also like to thank my advisor, Professor Roger Khayat, for his suggestions during the yearly progress report. I also thank the Advanced Fluid Mechanics (AFM) group members for the support and share of information.

I would like to express my gratitude to Dr. Leigh Orf of Wisconsin University for his assistance in setting up cloud model 1 (CM1). With his assistance, I was able to learn the fundamentals of LINUX software and set up CM1 for my simulations.

Finally, I would like to thank the examiners for their time, the Natural Sciences and Engineering Research Council (NSERC) of Canada for the funding, and everyone who contributed directly or indirectly to the completion of this thesis, especially my wife Catarina Kondo, for her emotional and spiritual support during these pandemic times.
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List of Abbreviations

AGL  Above Ground Level
CFD  Computational Fluid Dynamics
CM1  Cloud Model 1
CS   Cooling Source
COHMEX  Cooperative Huntsville Meteorological Experiment
ELR  Environmental Lapse Rate
IJ   Impinging Jet
JAWS Joint Airport Weather Studies
LES  Large Eddy Simulation
NIMROD Northern Illinois Meteorological Research on Downbursts
SCOUT Severe Convective Outflow in Thunderstorms
SGS  Subgrid scale
SHARCNET Shared Hierarchical Academic Research Computing Network
TASS Terminal Area Simulation System
TKE  Turbulent Kinetic Energy
WIST Wind Simulation and Testing
WP   Wind and Port
WPS  Wind, Port, and Sea
URANS Unsteady Reynolds Averaged Navier-Stokes
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<thead>
<tr>
<th>Symbol</th>
<th>Description</th>
<th>Unit</th>
</tr>
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<tbody>
<tr>
<td>A</td>
<td>Area</td>
<td>$[m^2]$</td>
</tr>
<tr>
<td>ADV</td>
<td>Advection operator</td>
<td>[-]</td>
</tr>
<tr>
<td>B</td>
<td>Buoyancy</td>
<td>$[m/s^2]$</td>
</tr>
<tr>
<td>$c_\varepsilon$</td>
<td>Turbulence dissipation stability constant</td>
<td>[-]</td>
</tr>
<tr>
<td>$c_p$</td>
<td>Specific heat of air at constant pressure</td>
<td>$[J/(kg K)]$</td>
</tr>
<tr>
<td>C(t)</td>
<td>Circulation as a function of time</td>
<td>$[m^2/s]$</td>
</tr>
<tr>
<td>$D_u$</td>
<td>Optional diffusive tendency terms in the $u$-equation</td>
<td>$[m/s^2]$</td>
</tr>
<tr>
<td>$D_v$</td>
<td>Optional diffusive tendency terms in the $v$-equation</td>
<td>$[m/s^2]$</td>
</tr>
<tr>
<td>$D_w$</td>
<td>Optional diffusive tendency terms in the $w$-equation</td>
<td>$[m/s^2]$</td>
</tr>
<tr>
<td>$e$</td>
<td>Subgrid turbulence kinetic energy</td>
<td>[J]</td>
</tr>
<tr>
<td>$f$</td>
<td>Coriolis parameter</td>
<td>$[s^{-1}]$</td>
</tr>
<tr>
<td>Fr</td>
<td>Densimetric Froude number ($Fr = \frac{V_0}{\sqrt{R_o g \frac{\Delta \rho}{\rho}}}$)</td>
<td>[-]</td>
</tr>
<tr>
<td>g</td>
<td>Acceleration due to gravity</td>
<td>$[m/s^2]$</td>
</tr>
<tr>
<td>g(t)</td>
<td>The growth of the cooling rate.</td>
<td>$[K/s]$</td>
</tr>
<tr>
<td>$h_x$</td>
<td>Horizontal half-width of the CS in the $x$-direction</td>
<td>[m]</td>
</tr>
<tr>
<td>$h_y$</td>
<td>Horizontal half-width of the CS in the $y$-direction</td>
<td>[m]</td>
</tr>
<tr>
<td>$h_z$</td>
<td>Vertical half-width of the CS in the $z$-direction</td>
<td>[m]</td>
</tr>
<tr>
<td>$h_c$</td>
<td>Vertical location of the CS centre from the ground</td>
<td>[m]</td>
</tr>
<tr>
<td>Symbol</td>
<td>Description</td>
<td>Unit</td>
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<tr>
<td>---------</td>
<td>-----------------------------------------------------------------------------</td>
<td>------------</td>
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<tr>
<td>( H_{\text{max}} )</td>
<td>Height of the volume outside the CS</td>
<td>[m]</td>
</tr>
<tr>
<td>( K_h )</td>
<td>The scalar eddy diffusivity</td>
<td>( \text{m}^2/\text{s} )</td>
</tr>
<tr>
<td>( K_m )</td>
<td>The eddy viscosity for momentum</td>
<td>( \text{kg/s} \cdot \text{m} )</td>
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<tr>
<td>( I )</td>
<td>Turbulent mixing length</td>
<td>[m]</td>
</tr>
<tr>
<td>( N_m^2 )</td>
<td>Brunt-Väisälä frequency</td>
<td>[Hz]</td>
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<tr>
<td>( N_u )</td>
<td>Newton relaxation terms in the u-equation</td>
<td>( \text{m/s}^2 )</td>
</tr>
<tr>
<td>( N_v )</td>
<td>Newton relaxation terms in the v-equation</td>
<td>( \text{m/s}^2 )</td>
</tr>
<tr>
<td>( N_w )</td>
<td>Newton relaxation terms in the w-equation</td>
<td>( \text{m/s}^2 )</td>
</tr>
<tr>
<td>( p )</td>
<td>Total pressure</td>
<td>[Pa]</td>
</tr>
<tr>
<td>( p_0 )</td>
<td>Base state pressure</td>
<td>[Pa]</td>
</tr>
<tr>
<td>( q(x,y,z,t) )</td>
<td>Cooling rate function of the forcing CS</td>
<td>[K/s]</td>
</tr>
<tr>
<td>( q_{\text{max}} )</td>
<td>Magnitude of the CS peak cooling rate.</td>
<td>[K/s]</td>
</tr>
<tr>
<td>( Q )</td>
<td>Volume of the forcing CS</td>
<td>( \text{m}^3 )</td>
</tr>
<tr>
<td>( Q_{\text{in}} )</td>
<td>Volume inside the ellipsoidal CS</td>
<td>( \text{m}^3 )</td>
</tr>
<tr>
<td>( Q_{\text{out}} )</td>
<td>Volume outside the ellipsoidal CS</td>
<td>( \text{m}^3 )</td>
</tr>
<tr>
<td>( r )</td>
<td>Radial distance from the centre of the downburst.</td>
<td>[m]</td>
</tr>
<tr>
<td>( r_{\text{max}} )</td>
<td>The radial distance at which the peak wind speed occurs</td>
<td>[m]</td>
</tr>
<tr>
<td>( R )</td>
<td>Gas constant for dry air</td>
<td>[J/(kg K)]</td>
</tr>
<tr>
<td>( R )</td>
<td>Non-dimensional scaled radius of the ellipsoidal CS</td>
<td>[ - ]</td>
</tr>
<tr>
<td>( R_d )</td>
<td>Radius of the downdraft column</td>
<td>[m]</td>
</tr>
<tr>
<td>Variable</td>
<td>Description</td>
<td>Unit</td>
</tr>
<tr>
<td>----------</td>
<td>-------------</td>
<td>------</td>
</tr>
<tr>
<td>(Re)</td>
<td>Reynolds number ((Re = \frac{v_0 R_0}{v}))</td>
<td>[-]</td>
</tr>
<tr>
<td>(R_0)</td>
<td>Equivalent spherical radius or characteristic length</td>
<td>[m]</td>
</tr>
<tr>
<td>(R_{\text{max}})</td>
<td>Maximum radius of the circle enclosed in the domain</td>
<td>[m]</td>
</tr>
<tr>
<td>(S)</td>
<td>Rate-of-strain tensor</td>
<td>([s^{-1}])</td>
</tr>
<tr>
<td>(S_{ij})</td>
<td>Main strain tensor</td>
<td>([s^{-1}])</td>
</tr>
<tr>
<td>(S^2)</td>
<td>Deformation</td>
<td>[m²]</td>
</tr>
<tr>
<td>(t)</td>
<td>Simulation time</td>
<td>[s]</td>
</tr>
<tr>
<td>(t_{\text{max}})</td>
<td>Time in which peak radial speed occurs</td>
<td>[s]</td>
</tr>
<tr>
<td>(T)</td>
<td>Temperature</td>
<td>[K]</td>
</tr>
<tr>
<td>(T_0)</td>
<td>Characteristic time scale</td>
<td>[s]</td>
</tr>
<tr>
<td>(T_u)</td>
<td>Tendency from subgrid turbulence in the u-equations</td>
<td>[m/s²]</td>
</tr>
<tr>
<td>(T_v)</td>
<td>Tendency from subgrid turbulence in the v-equations</td>
<td>[m/s²]</td>
</tr>
<tr>
<td>(T_w)</td>
<td>Tendency from subgrid turbulence in the w-equations</td>
<td>[m/s²]</td>
</tr>
<tr>
<td>(u)</td>
<td>Spatially filtered orthogonal velocity in the x-direction</td>
<td>[m/s]</td>
</tr>
<tr>
<td>(u_r)</td>
<td>Radial wind speed</td>
<td>[m/s]</td>
</tr>
<tr>
<td>(u_{r,\text{max}})</td>
<td>Peak radial wind speed</td>
<td>[m/s]</td>
</tr>
<tr>
<td>(v)</td>
<td>Spatially filtered orthogonal velocity in the y-direction</td>
<td>[m/s]</td>
</tr>
<tr>
<td>(V_0)</td>
<td>Characteristic velocity scale</td>
<td>[m/s]</td>
</tr>
<tr>
<td>(V_{\text{max}})</td>
<td>Maximum velocity</td>
<td>[m/s]</td>
</tr>
<tr>
<td>(V_H)</td>
<td>Instantaneous horizontal wind speed</td>
<td>[m/s]</td>
</tr>
</tbody>
</table>
\( w \) Spatially filtered orthogonal velocity in the z-direction \( [\text{m/s}] \)

\( x \) Horizontal position in the computational domain \( [\text{m}] \)

\( x_0 \) x-position of the centre of ellipsoidal CS \( [\text{m}] \)

\( y \) Horizontal position in the computational domain \( [\text{m}] \)

\( y_0 \) y-position of the centre of ellipsoidal CS \( [\text{m}] \)

\( z \) Vertical position in the computational domain \( [\text{m}] \)

\( z_0 \) z-position of the centre of ellipsoidal CS \( [\text{m}] \)

\( z_0 \) Ground roughness length \( [\text{m}] \)

\( z_{\text{max}} \) The height at which the peak wind speed occurs \( [\text{m}] \)

\( \alpha \) Generic variable in the advection equation \( [\ ] \)

\( \Gamma \) Temperature lapse rate \( [\text{K/m}] \)

\( \Gamma_d \) Dry adiabatic lapse rate \( [\text{K/m}] \)

\( \Delta \) Spatial filter size \( [\text{m}] \)

\( \varepsilon \) Turbulent kinetic energy dissipation rate \( [\text{J/kg/s}] \)

\( \theta \) Potential temperature \( [\text{K}] \)

\( \theta_p \) Density potential temperature \( [\text{K}] \)

\( \theta_{p0} \) Density base-state potential temperature \( [\text{K}] \)

\( \theta' \) Potential temperature perturbations \( [\text{K}] \)

\( \nu \) Kinematic viscosity \( [\text{m}^2/\text{s}] \)
<table>
<thead>
<tr>
<th>Symbol</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\pi$</td>
<td>Non-dimensional pressure ($\pi \equiv \left( \frac{p}{p_0} \right)^{\frac{R}{\rho}}$)</td>
</tr>
<tr>
<td>$\pi_0$</td>
<td>Base-state non-dimensional pressure.</td>
</tr>
<tr>
<td>$\pi'$</td>
<td>Non-dimensional pressure perturbations</td>
</tr>
<tr>
<td>$\rho$</td>
<td>Ambient density [kg/m$^3$]</td>
</tr>
<tr>
<td>$\rho_0$</td>
<td>Base-state density [kg/m$^3$]</td>
</tr>
<tr>
<td>$\bar{\rho}_{\text{in}}$</td>
<td>Spatially averaged density inside the CS. [kg/m$^3$]</td>
</tr>
<tr>
<td>$\bar{\rho}_{\text{out}}$</td>
<td>Spatially averaged density outside the CS. [kg/m$^3$]</td>
</tr>
<tr>
<td>$\tau_{ij}$</td>
<td>Subgrid shear stresses [kg/(ms$^2$)]</td>
</tr>
<tr>
<td>$\tau_{\text{t}^0}$</td>
<td>Turbulent fluxes for the potential temperature [kg•K/(m$^2$s)]</td>
</tr>
<tr>
<td>$\Omega$</td>
<td>Rate-of-rotation tensor [s$^{-1}$]</td>
</tr>
<tr>
<td>$\Delta x$</td>
<td>Grid spacing in the x-direction (East – West) [m]</td>
</tr>
<tr>
<td>$\Delta y$</td>
<td>Grid spacing in the y-direction (North – South) [m]</td>
</tr>
<tr>
<td>$\Delta z$</td>
<td>Grid spacing in the z-direction (vertical direction) [m]</td>
</tr>
<tr>
<td>$\Delta \rho$</td>
<td>Density difference [kg/m$^3$]</td>
</tr>
<tr>
<td>$\Delta \rho/\rho$</td>
<td>Non-dimensional density difference [ - ]</td>
</tr>
</tbody>
</table>
Chapter 1

1 Introduction

This chapter defines and describes the main characteristics of the downburst phenomenon caused by thermodynamic cooling due to precipitation in the convective clouds during thunderstorms. The chapter also presents the motivation and objectives of this research, as well as an overview of current knowledge and knowledge gaps.

1.1 Thunderstorms and downdrafts

A thunderstorm is a convective cloud, also known as cumulonimbus cloud, that forms because of rising warm moist air in a conditionally or absolutely unstable environment (Figure 1.1) (Ahrens & Henson, 2019). The cumulonimbus cloud produces rainfall, lightning, large hail, and downdrafts (Cotton et al., 2011). The downdraft, a cooled column of sinking air formed during a storm, is driven by negative buoyancy due to the thermodynamic cooling induced by the evaporation, melting, and sublimation of the water droplets or ice crystals in the cloud (Orf et al., 2014). The downdraft velocity is often increased by the rain during a thunderstorm (Figure 1.1). Rain may not reach the surface due to the rapid evaporation or the high speed of the warm and moist updraft air, resulting in the phenomenon known as virga (Figure 1.1) (Ahrens & Henson, 2019).

Figure 1.1: A simplified model illustrating a thunderstorm (Cumulonimbus cloud) in the atmosphere. Adapted from Ahrens and Henson (2019).
Unlike updrafts that transport warm air upwards to form the thunderstorm clouds, downdrafts transport air downward and are responsible for hazardous weather (Doswell III, 2001). When a downdraft reaches the surface, it spreads out horizontally, causing outflows in all directions. The leading edge of the outflowing air is called the gust front (Figure 1.1) (Ahrens & Henson, 2019).

1.2 Atmospheric stability

The stability of the atmosphere is crucial in the formation of thunderstorms. As previously stated, a cumulonimbus cloud forms in a conditionally or absolutely unstable environment (Ahrens & Henson, 2019). Atmospheric stability is determined based on the lapse rate of the atmosphere, also known as environmental lapse rate (ELR or \( \Gamma \)), which is defined as the negative of the rate at which the environmental temperature decreases with altitude (Figure 1.2) (Ahrens & Henson, 2019). The ELR determines whether the updraft air will rise high enough and cool sufficiently to form the thunderstorm clouds (Jacobson, 2005), and it is positive in the lowest region of the atmosphere, known as the troposphere \( (z < 10 \text{ km}) \), which is the region of interest for thunderstorm studies.

The atmosphere can be classified as stable, conditionally unstable, or absolutely unstable, based on the magnitude of the ELR. An average ELR of 6.5 K/km or less indicates a stable atmosphere, whereas one of 9.8 K/km or higher indicates an absolutely unstable atmosphere (Figure 1.2). The ELR of a conditionally unstable atmosphere ranges from 6.5 to 9.8 K/km (Ahrens & Henson, 2019) (Figure 1.2). In a stable atmosphere, air resists both upward and downward motion (Ahrens & Henson, 2019). As a result, when air is forced upward, it spreads horizontally, which is the reason cumulonimbus clouds (shown in Figure 1.1) do not form in a stable environment (Ahrens & Henson, 2019). However, they do form in a conditionally unstable atmosphere and tend to produce strong downdrafts denominated downburst (Anderson & Straka, 1993; Orf, 1997; Mason et al., 2009). Absolutely unstable atmosphere, which is uncommon, is also associated with the development of severe thunderstorms (Ahrens & Henson, 2019). The ELR of 9.8 K/km is denominated dry adiabatic lapse rate, and it is the value at which the temperature of an air parcel would decrease (upward motion) or increase (downward motion) adiabatically.
Jacobson, 2005). The 6.5 K/km is the moist adiabatic lapse rate, which is when the air is saturated and releases latent heat adiabatically (Ahrens & Henson, 2019).

![Figure 1.2: Representation of the atmospheric stability regions defined by the lapse rate. Adapted from Ahrens and Henson (2019).](image)

1.3 The downburst

A downburst is a natural phenomenon that occurs during thunderstorms, creating hazards and damage to infrastructures due to the strong winds produced (Mason et al., 2009). Fujita (1978) defined a downburst as a strong downdraft inducing an outward burst of damaging winds on or near the ground. Figure 1.3 depicts a downburst, where the downdraft and the horizontal vortex rings after the impingement on the ground are observed due to precipitation and flying dust. The strong wind gusts generated pose hazards to aviation, identified as the cause of aircraft crashes from the early 1960s to the late 1990s. One of the major crashes with large number of casualties (killing 112 and injuring 12) was the crash of the Boeing 727 Aircraft in 1975 when landing at the New York’s John F. Kennedy (JFK) international airport (Wilson & Wakimoto, 2001). During landing, the aircraft experienced an increase in the lift force, increasing its altitude and affecting its desired path as seen in
Figure 1.4. As the altitude during landing and takeoff is low, abrupt changes in the aircraft’s altitude can lead to a crash because it can take significant time to correct the situation.

Figure 1.3: Wet downburst in a convective storm over Oklahoma City, on July 26, 1978. Adapted from Bluestein (2013).

Figure 1.4: Aircraft response to downburst during landing. Based on a figure from Alahyari (1995).
Downbursts are characterized by the divergent and generally straight winds on the ground (Fujita, 1978) and subdivided based on the scale of the damaging winds. Downbursts with a damaging pattern less than 4 km are denominated microbursts, whereas those with a higher than 4 km damaging pattern are denominated macrobursts (Fujita, 1985). Microbursts are short-lived and can last 5 to 10 min reaching a peak wind speed of 75 m/s, whilst macrobursts can last from 5 to 30 min with a peak wind speed of 60 m/s (Fujita, 1985). Due to the short life and small size of microbursts, they are sometimes difficult to detect by non-Doppler radars or anemometers located on the ground (Fujita, 1985). Based on the amount of precipitation observed on the ground, downbursts can be classified into wet and dry downbursts. Wet downbursts, observed mostly in wet regions of the world, are those in which the raindrops do not evaporate completely before reaching the ground. This is due to the small altitude of the base of the cloud generating the downdraft (Figure 1.5). On the contrary, in dry downbursts, the altitude of the base of the cloud generating the downdraft is sufficiently high to allow the evaporation of the raindrops before the downdraft reaches the ground (Fujita, 1985). The downdraft can reach the ground even without raindrops because it has achieved the necessary downward momentum to reach the ground by the time precipitation has evaporated (Fujita, 1985).

Figure 1.5: Schematic views of a wet and a dry downburst. Based on a figure from Fujita (1985).
The downburst is sometimes confused with a tornado due to the similarity between the two phenomena. Examination of aerial photographs revealed that damage due to strong downbursts is often identical to those due to tornados (Fujita, 1978). However, though downbursts frequently occur in the vicinity of tornadoes, the flow pattern is different. Downburst flows have straight winds that cause several trees in a forest to be pushed in one direction (Figure 1.6), whilst tornadoes have strong swirling drafts (Hsu & Uzal, 1990). In addition, the vortices are different since those observed during a downburst are horizontal and those observed during a tornado are vertical, as shown in Figure 1.7.

Figure 1.6: Trees blown down in one direction by a downburst. Adapted from Fujita (1981).

Figure 1.7: Differences in flows between downburst (microburst) and tornado. Adapted from Fujita (1985).
Wolfson (1988) illustrated the downburst in four stages: the descending stage, the contact stage, the mature stage, and the breakup stage. The descending stage (Stage I) is when the midair microburst descends before it impinges on the ground. Small vortices are already visible and the maximum wind speed of the sinking air at this stage is observed when it is near the ground. The contact stage (Stage II) is when the downdraft impinges the ground before it bursts out radially. Vortices are still visible during the contact stage, and the downdraft velocity is near zero. The mature stage (Stage III) is when the downdraft spreads out, stretching the ring vortices radially. This stage is reached only 5 to 10 min after the formation of the downburst, and the damaging winds and gust fronts are observed in this stage (Hsu & Uzal, 1990). In the breakup stage (Stage IV), the vortices dissipate leading to the burst swaths. The four stages explained are illustrated in Figure 1.8.

![Figure 1.8: Schematic illustrating the four stages of the evolution of a downburst.](image-url)
1.4 Literature review

This section provides an overview of the current and previous relevant research on downbursts, including field projects and models used to investigate the structure of downburst outflows.

1.4.1 Field projects to study downbursts

The aircraft accident on June 24, 1975, at the JFK airport, spurred research into downbursts to understand the structure and dynamics of such events (Bluestein, 2013). The definition of the downburst and the field projects carried out by Fujita and his collaborators marked an important advance in the meteorological studies of the downburst event. The Northern Illinois Meteorological Research on Downburst (NIMROD), the first field project to detect a downburst, used a Doppler radar to observe the three-dimensional structure of a real downburst airflow (Wilson & Wakimoto, 2001). It was observed from the NIMROD project that the maximum horizontal velocity reached was 31 m/s, located less than 100 m above the ground (Wilson & Wakimoto, 2001). NIMROD detected approximately 50 microbursts that led to the collection of full-scale downburst data that is often compared with data from experiments and numerical simulations of downbursts. The NIMROD project, however, failed to provide a clearer understanding of the structure and evolution of downbursts. The use of the Doppler radar is limited because a few downburst events occur close enough to the radar beam to resolve the vertical structure of the outflow wind fields (Anderson et al., 1992).

The Joint Airport Wind Shear (JAWS) Project experiment conducted in 1982 was a more comprehensive field project than NIMROD (Wilson & Wakimoto, 2001). The JAWS experiments included a radar network (constituted by three Doppler radars), radiosonde equipment, and other instruments that were specifically designed to collect high-resolution radar and surface data that allows the study of three-dimensional downburst airflow structure (Srivastava, 1985; Hjelmfelt et al., 1989). The JAWS project also helped in detecting and observing the vortices of the leading edge of the downburst outflow, as seen in Figure 1.9. The results of the experiments during the JAWS project and the limitations of the NIMROD observational studies induced several wind engineers and meteorologists
(Wilson et al., 1984; Srivastava, 1985, 1987; Hjelmfelt, 1987, 1988; Proctor, 1989, Brison & Brun, 1991, Cooper et al., 1993) to turn to numerical models (to be discussed in the next section) to investigate downbursts.

The complexities of the turbulence during a thunderstorm and a downburst event thwart the establishment of a physically realistic and simple model that analyzes the entire flow structure and meets the requirements of both wind engineering and atmospheric science (Gunter & Schroeder, 2015). This has induced more field projects such as the Severe Convective Outflow in Thunderstorm (SCOUT) (Gunter & Schroeder, 2015), as well as the two European Union (EU) projects: “Wind and Ports” (WP, 2009 – 2012) (Solari et al., 2012) and “Wind, Ports, and Sea” (WPS, 2013 - 2015) (Repetto et al., 2018). WP and WPS projects used anemometer monitoring networks comprised of 28 ultrasonic anemometers mounted 20 m AGL and three lidar wind profiles to conduct a field measurement of the downburst event that occurred in the Livorno coast in 2012 (Burlando et al., 2017). The peak velocity observed ranged between 15 – 18 m/s (Burlando et al., 2017). The SCOUT project, which used mobile Doppler radars and surface measurement stations, collected

![Vortex](image)

**Figure 1.9:** Sequence of two photos showing the vortex behind the leading edge of the downburst outflow, during the JAWS project in 1982. Adapted from Fujita (1985).
full-scale data with high-resolution that produced normalized vertical velocity profiles of the maximum storm speed like those observed in Mason et al. (2009) numerical simulations (Gunter & Schroeder, 2015). The SCOUT project aided in visualizing the vertical velocity profile and validating the utility of simple numerical models (Gunter & Schroeder, 2015), whereas the WP and WPS projects provided more insight into the downburst’s real meteorological properties (Burlando et al., 2017).

Despite promising results in the field measurement of real downburst events, this method has some limitations and drawbacks. The field project costs are very high because more than one radar is required to observe the complex and complicated structures of a downburst (Anderson et al., 1992). Furthermore, downbursts are difficult to predict, occur quickly, and are short-lived, which thwarts the study of the mechanisms underlying their formation. Field studies are limited to observation and data collection since sensitive analysis about the effects of thermodynamic variables — environmental lapse rate, the rainwater mixing, and the relative humidity of the environment — on the downburst event is difficult to conduct. These limitations and disadvantages are overcome by using models to study the development of the downdraft, the velocity profile, and the mechanisms underlying intense downdrafts. These models can then be validated by comparing them to the full-scale data collected in field projects.

1.4.2 Models for downburst simulation

Models, whether numerical or experimental, are used to investigate real engineering problems on a small or large scale and have been extensively used in the study of downburst since Fujita’s early studies (Fujita, 1978, 1985; Fujita & Wakimoto, 1981). These experimental and numerical models have added to our understanding of the structure and dynamics of the downburst outflows. Furthermore, these downburst simulations aid in the understanding of the vertical and horizontal velocity profiles, as well as the microphysics of the clouds that produce downbursts.

1.4.2.1 Liquid release model

The liquid release model, also denominated as the density-driven model, is one of the experimental methods. As the name implies, the method entails releasing a fluid denser
than the ambient fluid contained in a tank, resulting in a downdraft that descends to the ground surface, as shown in Figure 1.10 (Lundgren et al., 1992). Lundgren et al. (1992) released saltwater into a freshwater tank to model a downburst, whereas Alahyari and Longmire (1995) used a solution of water and glycerol as the ambient fluid because glycerol is odorless and remains transparent when left in a tank for a week. An aqueous solution of potassium dihydrogen phosphate was used as the denser fluid due to the fixed density of the solution (Alahyari & Longmire, 1995). Lundgren et al. (1992) developed the scaling parameters — length scale \((R_0)\), velocity scale \((V_0)\), and time scale \((T_0)\) — that represent the geometry and the forcing of the liquid release experiments conducted by many investigators (Lundgren et al., 1992; Alahyari & Longmire, 1994, 1995; Yao & Lundgren, 1996; Babaei, 2018; Graat, 2020; Babaei et al., 2021; Jariwala, 2021).

\[
R_0 = \left( \frac{3Q}{4\pi} \right)^{\frac{1}{3}} \tag{1.1}
\]

\[
T_0 = \left( \frac{R_0 \rho}{g \Delta \rho} \right)^{\frac{1}{2}} \tag{1.2}
\]

\[
V_0 = \frac{R_0}{T_0} \tag{1.3}
\]

where \(Q\) is the volume of the source releasing the downdraft, \(g = 9.81 \text{ m/s}^2\) is the constant of gravity, \(\rho\) is the density of the ambient fluid, and \(\Delta \rho / \rho\) is the non-dimensional density difference (percentage of density difference) between the released and the ambient fluid.

There is no established fluid to be used for this method. If laser Doppler velocimetry (LDV) or particle image velocimetry (PIV) is used, the fluids should be chosen so that the index of refraction remains uniform when the two fluids are mixed. Variations in the refractive index within the flow, even as small as 0.0002, can lead to damaged PIV images (Alahyari & Longmire, 1994). Furthermore, for the experiments to be carried out, a certain density and viscosity percentage difference between the downburst fluid and the ambient fluid must be achieved. Lundgren et al. (1992) experiments suggested that experiments of density difference percentages ranging from 1 to 10% could be carried out. Babaei (2018)
used density percentage difference values ranging from 1.95 to 5.51% while Graat (2020) and Jariwala (2021) used 3.37% in recent liquid release experiments.

Figure 1.10: Experimental modeling of downburst by dense liquid release. Planar laser-induced fluorescence (PLIF) images of the evolution of a stationary downburst. Adapted from Babaei et al. (2021).

Without a doubt, experimental models have aided in the simulation of downburst events with outflow characteristics — the gust fronts, horizontal vortices before and after the downdraft impingement — like those observed in JAWS projects, as seen in Figure 1.10. Furthermore, the method is not solely limited to stationary downburst; it has also been adapted to traveling downburst events (Jariwala, 2021). However, liquid release models have some disadvantages. Full-scale simulation of downbursts is not possible because
liquid release models are limited to small length scale experiments such as 1:9000 – 1:45000 (Lundgren et al., 1992), 1:25000 (Alahyari & Longmire, 1995), 1:16000 (Babaei, 2018; Graat, 2020), 1:5500, and 1:10000 (Jariwala, 2021). In addition, the obtained velocity is very low (Lin et al., 2007). These disadvantages may be resolved by modeling the downburst using either the empirical approach, the impinging jet (IJ) model, or the Cloud model (CM). The use of an empirical approach to model a downburst is uncommon, used to date by a few researchers (Holmes & Oliver, 2000; Chay et al., 2006; Abd-Elaal et al., 2013) so is not discussed further here.

1.4.2.2 Impinging Jet models

The impinging jet (IJ) approach suggested by Fujita (1985) is another method of modeling a downburst. Adopted by many researchers (Brison & Brun, 1991; Selvan & Holmes, 1992; Cooper et al. 1993; Letchford & Illidge, 1998; Wood et al., 2001; Hall et al., 2003; Chay et al., 2006; Kim & Hangan, 2007, Zhang et al., 2013; Romanic et al., 2019), the IJ model has proved to be a good approach to model a downburst, either experimentally or numerically, leading to more intense outflows than those produced by liquid release methods (Lin et al., 2007). Experimentally, a microburst simulator constituted by a fan or other flow generator equipment is used to provide the initial momentum to the flow, which descends and impinges on the ground plate and spreads out radially, as depicted in Figure 1.11. The IJ approach has produced results that reasonably agreed with the data collected from field studies of downburst events such as NIMROD (Fujita, 1985) and JAWS (Hjelmfelt, 1988). Figure 1.12 shows the normalized velocity and height of different IJ model data (Letchford & Illidge, 1998; Selvan & Holmes, 1992; Oseguera & Bowles, 1988) and full-scale measurements from NIMROD (Fujita, 1985) and JAWS (Hjelmfelt, 1988), where it is seen that the IJ results fell in the range of full-scale measurements in JAWS (Hjelmfelt, 1988). Steady-state IJ models (Selvan & Holmes, 1992; Oseguera & Bowles, 1988), however, fail to capture transient features and lack the realistic physics encountered in downburst events because the primary driving mechanism of a real downburst is a negative buoyancy force and not an initial momentum (Vermeire et al., 2011a).
Figure 1.11: Microburst Simulator in Wind Simulation and Testing (WIST) Laboratory at Iowa State University. Adapted from Zhang et al. (2013).

Figure 1.12: Comparison of Impinging Jet model results with field measurements (Fujita, 1985; Hjelmfelt, 1988). Adapted from Wood et al. (2001).
Lin and Savory (2010) modelled meteorological downburst outflows with a plane wall jet from a rectangular slot rather than the commonly used radial wall jet from a round nozzle. The plane wall jet approach generated the plane wall jet by using a two-dimensional slot parallel to a solid boundary (Lin & Savory, 2010). A schematic of the plane wall jet is shown in Figure 1.13. A downburst outflow large enough for wind engineering analysis was generated, and the vertical velocity profile obtained from the wall jet fit well with the analytical velocity profile equation by Holmes and Oliver (2000). However, the outflow spreading rate was lower than the radial wall jet spreading rate, accounting for only 83% of the radial wall jet spreading rate (Lin, 2010). Further research is needed to examine the spreading rate and the decay of the outflow in the plane wall jet.

**Figure 1.13: Schematic of the Plane-wall jet. Adapted from Lin (2010).**

1.4.2.3 Cloud models

Cloud models approximate the real downburst events by attempting to replicate the thermodynamic cooling process observed during a real event (Vermeire et al., 2011a). The cloud model simulations can be divided into two categories: Those that include the simulation of the storm and the clouds that produce downbursts (full-cloud model) (Hjelmfelt et al., 1989; Straka & Orf, 1993; Orf et al., 2012, 2014), and those that do not. The full-cloud model simulations include the microphysics processes — clouds and precipitation — which are responsible for the thunderstorm producing the downburst. The simulation of the cumulonimbus cloud, which forms the downdraft during a thunderstorm,
can be seen in **Figure 1.14**. In those that do not simulate the clouds, there are two types: those initiated by imposing a precipitation source at the top of the domain (Srivastava, 1985, 1987; Proctor, 1988), and those that do not include precipitation at all but instead use a negatively buoyant cooling source (CS) model (Anderson et al., 1992; Orf et al., 1996; Orf & Anderson, 1999; Lin et al., 2007; Mason et al., 2009; Vermeire et al., 2011a,b; Oreskovic et al., 2018). The buoyant CS model replicates the effects of evaporation of rain and forces a dry downburst event. The cloud models that use the CS model are often denominated subcloud models.

![Cumulonimbus cloud](image)

**Figure 1.14**: A view of the thunderstorm cumulonimbus cloud and rain fields during a full-cloud model simulation of the downburst. Adapted from Orf et al. (2012).

Despite lacking microphysics, subcloud models have helped significantly in the understanding of downburst downdrafts and outflows. Anderson et al. (1992) used a three-dimensional subcloud model to simulate the dynamics of small-scale, near-surface flows that occur during a thunderstorm. Previous research (Hjelmfelt et al., 1989; Straka, 1989) suggested that realistic outflows could be generated by employing a downdraft forcing field composed of a simple space- and time-dependent cooling function which forces the model temperature field. Anderson et al. (1992) imposed a cooling function with an ellipsoidal geometric shape, horizontal half-widths of 1200 m, vertical half-widths of 1800 m, and a forcing peak cooling rate of -0.052 K/s to approximate the structure of those produced by
full-cloud model simulations. Orf et al. (1996) used the same CS model to investigate the morphology of colliding microbursts in a dry, hydrostatically balanced, stationary, and statically adiabatic environment. Lin et al. (2007) used a dry version of the Bryan Cloud Model (CM1) (Bryan, 2002), which employs the forcing CS by Anderson et al. (1992) to generate a realistic downburst by parameterizing the thermodynamic cooling found in downburst-producing thunderstorms. The results of the simulations using subcloud models were reasonably consistent with the results of the simulation using the impinging jet approach (Brison & Brun, 1991; Cooper et al., 1993; Wood et al., 2001; Kim & Hangan, 2007). **Figure 1.15** shows the evolution of an ideal downburst simulated using a subcloud model CM1 by Bryan (2002). **Figure 1.16** shows a chart summarizing the engineering methods commonly used to model a downburst, and **Table 1.1** shows the respective limitations summarized. The present research project uses a subcloud model with a forcing cooling source (Anderson et al., 1992) to initiate the downdraft. This was selected because some IJ models (Selvan & Holmes, 1992; Oseguera & Bowles, 1988) do not capture the buoyancy-driven effects that are observed in thunderstorms, while others fail in capturing the non-dimensional vorticity terms observed in CS models (Vermeire et al., 2011a). Furthermore, since the study focuses on the dynamics of the near-ground outflows of dry downbursts rather than the formation of the downdraft, the subcloud model is preferred over the computationally expensive full-cloud model.

![Figure 1.15: Simulation of a downburst using subcloud model with a forcing CS of peak cooling rate -0.08 K/s. t = 340 s.](image)
Figure 1.16: A chart demonstrating a summary of the downburst models.
Table 1.1: A summary of downburst models and their limitations.

<table>
<thead>
<tr>
<th>Downburst models</th>
<th>Limitations/disadvantages</th>
</tr>
</thead>
<tbody>
<tr>
<td>Experimental methods:</td>
<td>- Limited to small-scale simulations.</td>
</tr>
<tr>
<td>Liquid release models</td>
<td>- Low velocity outflow is generated.</td>
</tr>
<tr>
<td>(Lundgren et al., 1992; Alahyari &amp; Longmire, 1994, 1995; Babaei, 2018; Graat, 2020, Jariwala, 2021)</td>
<td>- Difficult to simulate different ELR.</td>
</tr>
<tr>
<td>Experimental and numerical IJ models</td>
<td>- Lack the physics encountered in downburst events and the primary driving mechanism.</td>
</tr>
<tr>
<td>(Brison &amp; Brison, 1991; Selvan &amp; Holmes, 1992; Wood et al., 2001; Hall et al., 2003; Zhang et al., 2013; Romanic et al., 2019)</td>
<td></td>
</tr>
<tr>
<td>Plane-wall Jet</td>
<td>- Outflow spreading rate is lower than the radial wall jet (typical IJ) outflow.</td>
</tr>
<tr>
<td>(Lin et al., 2007; Lin &amp; Savory, 2010)</td>
<td></td>
</tr>
<tr>
<td>Full-cloud models</td>
<td>- Negative buoyancy.</td>
</tr>
<tr>
<td>(Hjelmfelt et al., 1989; Straka &amp; Anderson, 1993; Orf et al., 2012, 2014)</td>
<td>- Computationally expensive</td>
</tr>
<tr>
<td></td>
<td>- Typically run at considerably lower resolution than subcloud models.</td>
</tr>
<tr>
<td></td>
<td>- The downburst may not occur. Need specific parameters or condition.</td>
</tr>
<tr>
<td>Cloud model using precipitation only</td>
<td>- More expensive than subcloud models</td>
</tr>
<tr>
<td>(Srivastava, 1985; Proctor, 1988)</td>
<td>- Very high vertical resolution is required near the ground to capture the temporally varying wind speed.</td>
</tr>
<tr>
<td></td>
<td>- Does not simulate the storm clouds.</td>
</tr>
<tr>
<td></td>
<td>- Negative buoyancy</td>
</tr>
<tr>
<td>Subcloud models</td>
<td>- Lack precipitation and the clouds producing downburst.</td>
</tr>
<tr>
<td>(Anderson et al., 1992; Orf et al., 1996; Lin et al., 2007; Mason et al., 2009; Vermeire et al., 2011; Oreskovic et al., 2018a, 2018b)</td>
<td>- Imposes a forcing CS model.</td>
</tr>
<tr>
<td></td>
<td>- Cannot simulate wet downbursts.</td>
</tr>
</tbody>
</table>

1.4.3 Investigation of downbursts using cloud models

Cloud models (CM) have been used to investigate the mechanisms underlying the formation of downbursts, its near-ground outflows, and the magnitude of the peak wind speed produced. Srivastava (1985) discovered that the magnitude of the downdraft's vertical air velocity increases as the atmospheric lapse rate, the rainwater mixing ratio at the top of the downdraft, and the relative humidity of the environment increase. It does,
however, decrease as the mixing of environmental air into the downdraft increases (Srivastava, 1985, 1987). Other studies (Proctor, 1988, 1989; Hjelmfelt, 1988) found the same results regarding the effects of atmospheric temperature, humidity, and precipitation on the formation of downbursts. Proctor (1988) found out that microbursts were primarily driven by cooling due to the evaporation of rain and the melting of the hail. This finding was due to the use of a subcloud model with an axisymmetric two-dimensional version of the Terminal Area Simulation System (TASS) to simulate an isolated downburst caused by the effects of falling precipitation. The isolated downdraft was initiated by setting a distribution of precipitation as the top boundary condition, which led to the increase in the mass and density of air as the precipitation fell in the domain. The increase in density induced negative buoyancy that created a downdraft, which was intensified by the microphysical cooling (Proctor, 1988). Hjelmfelt et al. (1988) also found out that including the loading and melting of graupel, along with the loading and evaporation of rain reproduced a more realistic downburst event than those that lacked precipitation.

Orf (1997) investigated the effects of the environmental lapse rate on the strength of a traveling downburst using a subcloud model. Instead of using precipitation, the downburst was initiated using the same approach as Anderson et al. (1992), by imposing an ellipsoidal forcing cooling source (CS) as seen in Figure 1.17 with a maximum cooling rate of -0.03 K/s. The elevation of the centre of the forcing CS, 2000 m ABL, was consistent with microburst simulations conducted by Knupp (1989) and Hjelmfelt et al (1989), which found out that downdraft initiation occurred below the melting level, around 2 km ABL (Orf, 1997). The simulations were carried out at lapse rates of 8.26 K/km, 7.76 K/km, and 6.76 K/km. Results showed that as the lapse rates decreased, the magnitude of the surface horizontal winds decreased, and the roll vortex circulation weakened (Orf, 1997). Furthermore, when simulated in the most stable environmental condition (the 6.76 K/km case), all roll vortices are absent (Orf, 1997). The decrease in peak wind speed was also observed by Mason et al. (2009) by using the same forcing CS model by Anderson et al. (1992) but with a smaller radius (500 m) and centre height (1000 m), and a higher maximum cooling rate of -0.08 K/s. As the lapse rate decreased from 9.80 K/km to 7.50 K/km, the peak speed decreased by 19% (Mason et al., 2009). Orf (1997) and Mason et al.
(2009) findings were found to be consistent with Proctor's (1989) axisymmetric simulations in an environment with a lapse rate higher than 5.5 K/km.

Subcloud models have also been used to study downburst lines (Orf et al., 1996; Vermeire et al., 2011b), which are defined as the simultaneous occurrence of two or more downburst events that are close enough to form a continuous line due to the collision of diverging outflows (Vermeire et al., 2011b). Vermeire et al. (2011b) carried out a parametric study of downburst lines using the CS model by Anderson et al. (1992), with large eddy simulation (LES) in the Bryan Cloud Model (CM1) (Bryan, 2002; Bryan & Fritsch, 2002). Results showed that downburst lines posed a greater hazard than isolated downbursts (Orf et al., 1996; Vermeire et al., 2011b). Hazard was quantified based on the peak horizontal wind speed below 50 m and the surface area exposed to the hazardous wind outflows (Vermeire et al., 2011b). The peak wind speed observed during downburst lines \( U_P \) was greater than the isolated downburst \( U_{P\text{base}} \), \( U_P = 1.55U_{P\text{base}} \), and the damaging surface area was 70% greater, which agreed with the qualitative analysis by Orf et al. (1996).

Vermeire et al. (2011a) and Oreskovic et al. (2018a) proposed a scaling method for isolated downbursts simulated using CM1 with a forcing CS model based on CS by Anderson et al.
(1992). The scaling method by Vermeire et al. (2011a) was based on the size of the vortex at the leading edge, instead of the peak speed and its corresponding height. The proposed scaling method assumed that the vortex generated at the leading edge was elliptical as depicted in Figure 1.18, where the vortex core diameters are $D_v$ and $H_v$, the height of the vortex core is $C_z$, and the locations of the maximum translating velocity are $x_{up}$ and $z_{up}$ (Vermeire et al., 2011a). This scaling method focuses more on the outflow region, where the maximum radial outflow and primary vortex are identified. Thus, this method is more appropriate for comparing different numerical models since the method is independent of the inlet conditions (Vermeire et al., 2011a). On the other hand, the scaling method proposed by Oreskovic et al. (2018a) consisted of implementing the dense liquid release model scaling (Lundgren et al., 1992) to downbursts simulated using subcloud models with the spatially and temporally dependent forcing CS model (Anderson et al., 1992). The peak speed, position, and time variables are non-dimensionalized using Lundgren et al. (1992) scaling parameters — spherical radius ($R_0$), velocity ($V_0$), and time ($T_0$) — derived for the constant density release model, showing that these scaling parameters are not solely limited to liquid release models (Oreskovic et al., 2018a).

![Figure 1.18: Leading vortex scaling parameters proposed by Vermeire et al. (2011a). Adapted from Vermeire et al. (2011a).](image)

Despite the progress and the fundamental findings of the downburst simulations using subcloud models, the simulations were limited as it did not include the entire cloud life cycle and structure of the downburst-producing thunderstorms that are observed in the real
downburst events (Hjelmfelt et al., 1989). Hjelmfelt et al. (1989) performed a two-dimensional (2D) full-cloud model simulation of downbursts using a domain of 19.2 km × 19.2 km, and a uniform grid spacing of 200 m. The simulations were performed using the atmospheric soundings taken in Denver in July 1982, which were favorable for the formation of downbursts (Caracena et al., 1983; Wakimoto, 1985). A cloud with a structure and height like those observed in field projects was simulated, with the cloud base occurring around 2.2 km AGL, and the top cloud reaching 9.6 km (Hjelmfelt et al., 1989). A maximum speed of 22 m/s was achieved at the surface which agreed well with the 25 m/s observed in JAWS microburst (Hjelmfelt, 1988; Roberts & Wilson, 1989). However, the results were limited since Hjelmfelt et al. (1989) modeled a 2D downburst storm only. This limitation was resolved by Straka and Anderson (1993), which used an isotropic grid resolution of 500 m in a full domain of size 25 km × 25 km × 19 km to simulate a microburst with structures like the documented storm on 20 July 1986 during the Cooperative Huntsville Meteorological Experiment (COHMEX). The simulation was initiated using atmospheric soundings during COHMEX days, taken near Redstone Arsenal, Alabama (Straka & Anderson, 1993). The storm simulated generated a microburst with a diameter size ranging from 2.5 km to 4 km, and the strongest low-level downdraft developed at an altitude of 1.4 – 1.9 km AGL (Straka & Anderson, 1993), which is close to the cloud base altitude, 2.2 km, in which the downdraft originated in Hjelmfelt et al. (1989) simulations. The evolution of the storm was similar to that observed by Hjelmfelt et al. (1989) and Roberts and Wilson (1989), with peak downdraft velocities ranging from 4 to 12 m/s, and peak wind outflows of 25 m/s occurring at 125 m AGL (Straka & Anderson, 1993).

A finer grid resolution was used by Orf et al. (2012, 2014) to simulate downburst-producing thunderstorms. The Bryan cloud model (CM1) (Bryan & Fritsch, 2002) was used over a computational domain of 92 km × 92 km × 14 km. A horizontal finer grid spacing Δx = Δy = 20 m with a vertically stretched mesh, where Δz = 5 m immediately above the ground, stretching to 95 m at the top of the model was applied. The simulation was initiated with a sounding identified by Brown et al. (1982) and Wakimoto (1985), which represents the condition leading to the formation of dry downbursts over the High Plains of the USA (Orf et al., 2012). As a result, thunderstorm clouds were simulated,
which produced a downburst with a maximum radial outflow wind speed of 35 m/s at an elevation of 50 m, at a radial location $r = 1500$ m (Orf et al., 2012; Oreskovic et al., 2018b).

Due to the high computational cost of post-processing three-dimensional (3D) data from full-cloud model simulations, Orf et al. (2012, 2014) developed a simple approach that could be used to estimate the peak wind speeds in 3D full-cloud model simulations. This simple approach carries out a circumferential statistical analysis at an imposed constant radius periphery representing an axisymmetric “template” over the data set (Figure 1.19), to relate the peak wind speeds to the average value around the periphery (Orf et al., 2012). As a result, the asymmetric outflow is transformed into a symmetric outflow, and each time step produces a single vertical plane $(r, z)$ of data with radial velocity $u_r$ and vertical velocity $u_z$ (Orf et al., 2014), with $r$ representing the radial distance from the centre of the impingement and $z$ the altitude. The circumferentially-averaged data can then be used to estimate the velocity profile near the ground, as well as the peak wind velocity, instead of using the complex cartesian 3D full data. Oreskovic et al. (2018a,b) utilized the circumferential averaging approach to post-process data from the subcloud model simulations when carrying out a parametric investigation of downburst using the CS model by Anderson et al. (1992). The results showed that the approach developed for full-cloud models also works for subcloud models and enables the comparison of both models (Orf et al., 2012; Oreskovic et al., 2018b).

The circumferential averaging approach suggests that simple subcloud models can be used to estimate the peak wind speed, limiting the need to run the computationally expensive full-cloud model simulations to obtain the near-ground peak wind profile (Orf et al., 2012, 2014). The success of this approach, however, depends on using a forcing CS with a specific template — which has yet to be investigated — that can generate a downburst with similar circumferentially-averaged peak wind profiles to those observed in downburst-producing thunderstorms. Oreskovic et al. (2018b) proposed that the suitable CS should have a radius of 650 m which is equivalent to the half of the downburst column observed in the full-storm simulations (Orf et al., 2012, 2014). In addition, the elevation of the CS was proposed to be at 2500 m, and the non-dimensional density difference $(\Delta \rho / \rho)$ due to the CS’s cooling rate set to 1.33% (Oreskovic et al., 2018b).
1.5 Knowledge gaps

An advancement in the use of cloud models to simulate a downburst can be seen in the research works discussed. However, there are some gaps in the current knowledge that need to be filled. One of the identified gaps is the correct use of the Lundgren et al. (1992) scaling parameters for cloud model simulations with a spatially and temporally dependent forcing CS model. Besides demonstrating that the scaling parameters derived by Lundgren et al. (1992) can be applied successfully to the CS model, Oreskovic et al. (2018a) proposed that the non-dimensional density difference ($\Delta \rho / \rho$) between the density inside and outside of the forcing ellipsoidal CS, which is a critical parameter for determining the Lundgren et al. (1992) scaling parameters, should be calculated by calculating the spatial average.
densities over the CS volume. However, this method has yet to be developed. The accurate computation of $\Delta \rho/\rho$ leads to the correct spherical radius $R_0$, velocity $V_0$, and time $T_0$, reinforcing that these scaling variables are not solely limited to experimental liquid release models. Another gap identified is in the simulation and analysis of downburst events using subcloud models with different environmental lapse rates (ELR). Despite the quantitative analysis by Orf (1997) and Mason et al. (2009) on the effect of ELR on the horizontal peak wind speed after the downdraft impinges on the ground, the effect on the radial outflow evolution has yet to be carried out. In addition, a detailed quantitative analysis to show how the magnitude of the peak radial wind speed changes when the ELR is changed, and how this change is affected by the downburst intensity (quantified by the peak cooling rate of the CS) is still needed. Also, a detailed quantitative analysis of the structure of the downburst when ELR is less than the adiabatic lapse rate needs to be conducted since previous analyses were qualitative (Proctor, 1988; Mason et al., 2009). Finally, the correct forcing CS template to use in subcloud models to produce downburst with the same profile and circumferentially-averaged near-ground peak wind speed as downburst-producing thunderstorms has yet to be investigated. This would allow CS models to be used efficiently to investigate downburst storms rather than the computationally expensive 3D full-cloud model simulations. The success of this method is dependent on using the correct ellipsoidal CS template.

1.6 Thesis motivation

The hazard that a downburst poses to aviation has been one of the main driving factors to investigate downburst outflows. From 1964 to 1975, 25 aviation accidents due to wind shear were identified, 13 of which were related to downburst during thunderstorms, leading to many investigations of the downburst outflows near the ground (Hahn, 1987). However, the advancement in technologies and radar equipment has greatly minimized aircraft accidents. For example, the last aircraft accident due to a downburst in the USA was recorded more than 20 years ago (Smith, 2014). Despite that, an in-depth analysis of the downburst outflows near the ground level is still necessary for applications in wind and structural engineering. Understanding the structure of the outflow near the ground before and after the impingement will help to improve the design of surface structures such as
buildings and electricity transmission lines, as well as reducing damage or collapses due to downbursts. The 2011 downburst event in Belém, Brazil, which resulted in the collapse of a 37-story building (Loredo-Souza et al., 2019), is an example of the threat they pose to surface structures. Therefore, investigation of downburst near-ground outflows remains a priority due to the extent of the damage caused to the surface structures.

1.7 Objectives

The main purpose of this research is to fill the gaps identified in the current knowledge and add to our understanding of the development of near-ground outflows. The following are specific objectives of the current research:

- Improve the implementation of the Lundgren et al. (1992) scaling parameters for simulations using a CS model. This involves developing a method that considers the spatial variation of the density inside and outside the forcing CS, to evaluate the non-dimensional density difference $\Delta \rho / \rho$. The temporal variation of the cooling rate of the ellipsoidal CS and the temporal variation of $\Delta \rho / \rho$ are investigated.

- Investigate the strength and the wind velocity profile of downburst outflows due to the change in the lapse rate of the environment. A quantitative analysis of the near-ground downburst outflows is carried out.

- Investigate a template for the forcing CS capable of generating near-ground downburst outflows like those obtained with full-cloud models.

1.8 Organization of the thesis

There are five chapters in the current thesis. The following is a synopsis of the chapters included.

Chapter 1 – This chapter introduces the phenomenon of downburst and provides background information from the literature. Furthermore, the chapter identifies and discusses current knowledge gaps in the literature, as well as the motivations and objectives of this research.
Chapter 2 – This chapter describes the Cloud model (CM1), which is the numerical model used in the current work. The methodology for carrying out the simulations and the approach for averaging the data circumferentially are presented.

Chapter 3 – This chapter covers the implementation of the Lundgren et al. (1992) scaling parameters for CS numerical simulations at different CS peak cooling rates. The chapter also presents a thorough investigation of the CS's temporal evolution and its cooling rate temporal variation.

Chapter 4 – This chapter discusses downburst events in different ambient conditions, focusing mainly on the environmental lapse rate. A quantitative study of the effect of the lapse rate on the downflow and the outflow peak speed is carried out.

Chapter 5 – This chapter investigates the best CS template to use for simulating downburst events like downburst-producing thunderstorms obtained from full-cloud model simulations by Orf et al. (2012, 2014). This chapter is meant to be a stand-alone chapter, representing a paper that will be submitted to the Journal of Wind Engineering and Industrial Aerodynamics.

Chapter 6 – This chapter presents a general conclusion and provides recommendations for future studies.

1.9 Summary

This chapter introduced the downburst, which is defined as a strong downdraft that impinges on the ground and spreads out radially. It was shown that downbursts may occur if the environment is conditionally unstable (6.5 K/km < Γ < 9.8 K/km) or absolutely unstable (Γ > 9.8 K/km) in rare cases. A detailed literature review was presented where the downburst models were discussed, with special attention given to the use of cloud models, since they capture the buoyancy-driven mechanism observed in thunderstorms better than impinging jet models (Vermeire et al., 2011a). The gaps in the literature were identified and the specific objectives of this research were presented, which is to investigate the
strength and the wind velocity profile of downburst outflows due to the change in the environmental lapse rate, improve the implementation of the Lundgren et al. (1992) scaling parameters for simulations using a CS model by Anderson et al. (1992), and investigate a template for the forcing CS capable of generating near-ground downburst outflows like those obtained with full-cloud models. The next chapter discusses the numerical model employed in the research.

1.10 References


2 Numerical model and methodology

This chapter introduces the numerical model, in general terms, employed in the subsequent chapters. It presents the cloud model CM1 (Bryan, 2002) and the cooling source (CS) model by Anderson et al. (1992) with the respective governing equations. The circumferential averaging approach by Orf et al. (2012, 2014), which is used for data post-processing in this research, is also presented here.

2.1 Description of the numerical model used

The cloud model used in this research is the latest version of the Cloud Model 1 (CM1), cm1r19.10. This version was simplified slightly to increase performance, reducing the computational cost by 10% on some platforms and with some compilers. CM1 is scientifically defined as a three-dimensional, nonhydrostatic, nonlinear, time-dependent numerical model designed specifically for the simulation of ideal cases of atmospheric phenomena (Bryan, 2002). The model is nonhydrostatic because it considers the vertical acceleration observed in realistic thunderstorms. CM1 conserves mass and energy better than other modern cloud models such as Advanced Regional Prediction System (ARPS) and Regional Atmospheric Modelling System (RAMS), and it was designed specifically for very large computational domain simulations (order of 10^9 grid points) using high resolution (Bryan, 2002).

CM1 solves the three spatially filtered orthogonal velocity (u, v, w) from the filtered Navier-Stokes equations (the large eddy simulation equations), including the non-dimensional pressure perturbations (\( \pi' \)), potential temperature perturbations (\( \theta' \)), and the mixing ratios of moisture variables (\( q_x \)), where the subscript \( x = l \) denotes liquid, \( x = v \) denotes vapor, and \( x = i \) denotes ice. The derivative terms in the governing equations are discretized, and a 6th order diffusion scheme (\( k_{diff} = 0.040 \)) (Wicker & Skamarock, 2002) is used to solve the advection (spatial) derivatives, as recommended by Oreskovic et al. (2018a), because it removes the instabilities caused by the premature development of fluctuations in the temperature field observed in the 5th order scheme (Oreskovic, 2016).
The 3rd order Runge-Kutta (RK3) time integration scheme is used to solve the temporal derivative terms. To solve the small-scale components that are not considered in the filtered Navier-Stokes equations, a subgrid-scale (SGS) turbulence closure based on Deardorff (1980) is used because it considers turbulence as anisotropic and unsteady, making it ideal for small grid resolution.

2.1.1 The governing equations of CM1 (Bryan, 2017)

The governing equations for velocity in CM1 are the filtered Navier-Stokes equations, which have been modified for meteorological phenomena application.

\[
\frac{\partial u}{\partial t} + c_p \theta_p \frac{\partial \pi'}{\partial x} = \text{ADV}(u) + f \ v + T_u + D_u + N_u \tag{2.1}
\]

\[
\frac{\partial v}{\partial t} + c_p \theta_p \frac{\partial \pi'}{\partial y} = \text{ADV}(v) - f \ u + T_v + D_v + N_v \tag{2.2}
\]

\[
\frac{\partial w}{\partial t} + c_p \theta_p \frac{\partial \pi'}{\partial z} = \text{ADV}(w) + B + T_w + D_w + N_w \tag{2.3}
\]

where \( c_p \) is the specific heat of dry air at constant pressure, \( f \) is the Coriolis parameter, which is ignored for downburst flows since the buoyancy force is more dominant than the Coriolis forces (Mason et al., 2009). \( \theta_p \) is the density potential temperature, and \( u, v, w \), denote the filtered orthogonal velocity components in the \( x \) (east-west), \( y \) (north-south), and \( z \) (vertical) directions respectively. The D, N, and T terms represent the optional tendencies from other diffusive processes, the Newtonian relaxation (i.e., Rayleigh damping), and the tendency from sub-grid turbulence respectively. As in most simulations, D is neglected for simplicity. ADV is the advection operator, defined in CM1 for a variable \( \alpha \) in the form:

\[
\text{ADV}(\alpha) = \frac{1}{\rho_0} \left[ -\nabla \cdot (\alpha \rho_0 \vec{V}) + \alpha \nabla \cdot (\rho_0 \vec{V}) \right] \tag{2.4}
\]

where \( \rho_0 \) is the base state density, \( \nabla = \left( \frac{\partial}{\partial x'}, \frac{\partial}{\partial y'}, \frac{\partial}{\partial z} \right) \) is the gradient operator, and \( \vec{V} \) is the velocity vector \((u, v, w)\). In cartesian coordinates, ADV \((\alpha)\) is given by
\[
\text{ADV}(\alpha) = \frac{1}{\rho_0} \left[ - \frac{\partial (\alpha \rho_0 u)}{\partial x} - \frac{\partial (\alpha \rho_0 v)}{\partial y} - \frac{\partial (\alpha \rho_0 w)}{\partial z} + \alpha \left( \frac{\partial (\rho_0 u)}{\partial x} + \frac{\partial (\rho_0 v)}{\partial y} + \frac{\partial (\rho_0 w)}{\partial z} \right) \right] \quad (2.5)
\]

The buoyancy \( B \) in Equation (2.3) is given in terms of the density potential temperature \( (\theta_\rho) \), which is defined as the potential temperature \( (\theta) \) that dry air would have to possess the same density as moist air (Emanuel, 1994).

\[
B = g \frac{\theta_\rho - \theta_{\rho 0}}{\theta_{\rho 0}} \quad (2.6)
\]

where subscript ‘0’ denotes the base state, and \( g = 9.81 \text{ m/s}^2 \) is the gravitational constant.

The potential temperature \( (\theta) \) is the temperature an air parcel obtains if it is brought adiabatically from its altitude to a standard reference surface pressure of 100,000 Pa (Jacobson, 2005). It stays constant if the air displaced adiabatically is unsaturated (Jacobson, 2005).

\[
\theta = T \left( \frac{100,000 \text{ Pa}}{p} \right)^{R/c_p} \quad (2.7)
\]

where \( T \) is the temperature variable and \( p \) is the total pressure. The potential temperature \( (\theta) \) is decomposed into a mean or base-state \( (\theta_0) \) and deviation from the mean or perturbation \( (\theta') \) such that \( \theta = \theta_0 + \theta' \). The potential temperature base state parameter is assumed constant with time and in hydrostatic balance, and the perturbations are determined by the governing equation

\[
\frac{\partial \theta'}{\partial t} = \text{ADV}(\theta) + T_\theta + D_\theta + N_\theta + \frac{1}{\pi c_p} \varepsilon + q(x, y, z, t) \quad (2.8)
\]

where the term \( \varepsilon \) denotes the dissipation rate associated with the increase in internal energy of the cooling source when kinetic energy is dissipated, and \( q(x, y, z, t) \) denotes the spatial and temporal cooling source function (to be discussed in the next section).

The non-dimensional total pressure, also called the Exner function (Jacobson, 2005), is defined by
The non-dimensional pressure is also decomposed into base-state ($\pi_0$) and perturbation ($\pi'$). The base-state ($\pi_0$) is assumed in hydrostatic balance, given by

$$\frac{d\pi_0}{dz} = -\frac{g}{c_p\theta_0}$$  \hspace{1cm} (2.10)

The governing equation for non-dimensional pressure perturbations ($\pi'$), considering a dry environment, is the following:

$$\frac{\partial \pi'}{\partial t} = \text{ADV}(\pi) - \frac{R}{c_v} \pi (\nabla \cdot \vec{V})$$  \hspace{1cm} (2.11)

where $R$ is the gas constant for dry air, $c_v$ is the specific heat at a constant volume, and $\pi$ is the non-dimensional total pressure.

The governing equations for the moisture components, $q_l$, $q_v$, $q_i$, are discussed in detail in section 2 of the CM1 governing equations documentation (Bryan, 2011), so they are not presented here. The turbulent tendencies due to the small-scale turbulence, $T_u$, $T_v$, and $T_w$, in Equation (2.1), (2.2), and (2.3) are formulated by the equations:

$$T_u = \frac{1}{\rho} \left[ \frac{\partial \tau_{11}}{\partial x} + \frac{\partial \tau_{12}}{\partial y} + \frac{\partial \tau_{13}}{\partial z} \right]$$  \hspace{1cm} (2.12)

$$T_v = \frac{1}{\rho} \left[ \frac{\partial \tau_{12}}{\partial x} + \frac{\partial \tau_{22}}{\partial y} + \frac{\partial \tau_{23}}{\partial z} \right]$$  \hspace{1cm} (2.13)

$$T_w = \frac{1}{\rho} \left[ \frac{\partial \tau_{13}}{\partial x} + \frac{\partial \tau_{23}}{\partial y} + \frac{\partial \tau_{33}}{\partial z} \right]$$  \hspace{1cm} (2.14)

where $(\tau_{ij})$ are the subgrid stress terms formulated by
\[ \tau_{ij} \equiv -\rho u'_i u'_j = \begin{bmatrix} -\rho u'u' & -\rho u'v' & -\rho u'w' \\ -\rho v'u' & -\rho v'v' & -\rho v'w' \\ -\rho w'u' & -\rho w'v' & -\rho w'w' \end{bmatrix} = 2\rho K_m S_{ij} \]

where \( K_m \) is the viscosity and \( S_{ij} \) is the strain tensor given by

\[ S_{ij} = \frac{1}{2} \left[ \frac{\partial u_i}{\partial x_j} + \frac{\partial u_j}{\partial x_i} \right] = \begin{bmatrix} \frac{1}{2} \frac{\partial u}{\partial x} & \frac{1}{2} \frac{\partial u + \partial v}{\partial y} & \frac{1}{2} \frac{\partial u + \partial w}{\partial z} \\ \frac{1}{2} \frac{\partial u}{\partial y} & \frac{1}{2} \frac{\partial v}{\partial x} & \frac{1}{2} \frac{\partial v + \partial w}{\partial z} \\ \frac{1}{2} \frac{\partial u}{\partial z} & \frac{1}{2} \frac{\partial w}{\partial x} & \frac{1}{2} \frac{\partial w}{\partial y} \end{bmatrix} \]

where \( u', v', \) and \( w' \) are the velocity perturbations. The turbulent fluxes for the potential temperature (\( \theta \)) are given by

\[ \tau_{i}^\theta \equiv \rho u'_i \theta' = -K_h \rho \frac{\partial \theta}{\partial x_i} \]

where \( K_h \) is turbulence diffusivity. The turbulent fluxes associated with moisture, \( \tau_i^{q_l}, \tau_i^{q_v}, \tau_i^{q_i} \) are discussed in detail by Bryan (2002).

\( K_m \) and \( K_h \) need to be determined via the method chosen when setting up CM1 for a given application. For the downburst simulation, the turbulent kinetic energy (TKE) subgrid-scale model is used to solve for \( K_m \) and \( K_h \), as discussed in the following section.

### 2.1.2 Subgrid-scale turbulence model

A turbulent kinetic energy scheme (TKE) is used as the subgrid-scale model to determine \( K_m \) and \( K_h \). The TKE scheme in CM1 is similar to that described by Deardorff (1980), where the eddy viscosity \( K_m \) and the eddy diffusivity \( K_h \) are determined from the relations

\[ K_m = c_m l e^{\frac{1}{2}} \]

\[ K_h = c_h l e^{\frac{1}{2}} \]
where \( e \) is the subgrid TKE, given by

\[
e = \frac{1}{2} u_i^t u_j^t \tag{2.20}
\]

and the predictive equation for \( e \) is

\[
\frac{\partial e}{\partial t} = \text{ADV}(e) + K_m S^2 - K_h N_m^2 + \frac{1}{\rho} \frac{\partial}{\partial x_i} \left( 2 \rho K_m \frac{\partial e}{\partial x_i} \right) - \varepsilon \tag{2.21}
\]

where \( \varepsilon \) is dissipation, parameterized as

\[
\varepsilon = \frac{c_\varepsilon e^2}{l} \tag{2.22}
\]

\( S^2 \) is the deformation, defined by

\[
S^2 = 2S_{ij}S_{ij} \tag{2.23}
\]

\( N_m^2 \) is the squared Brunt-Vaisala frequency which, for subsaturated air in CM1 simulations, is given by

\[
N_m^2 = \frac{g}{\partial \rho / \partial z} \tag{2.24}
\]

The parameters \( c_m, c_h, c_\varepsilon \), and the mixing length \( l \) in Equations (2.18), (2.19), and (2.22) must be specified to close the equations. In CM1, \( c_m \) is set to 0.10, and the other parameters are formulated to reduce subgrid-scale mixing when \( N_m^2 > 0 \).

\[
l = \left( \frac{2}{3} \frac{e}{N_m^2} \right)^{\frac{1}{2}} \tag{2.25}
\]

\[
c_h = 1 + 2 \frac{l}{\Delta} \tag{2.26}
\]

\[
c_\varepsilon = 0.2 + 0.787 \frac{l}{\Delta} \tag{2.27}
\]
where $\Delta$ is the spatial filter size, which is defined as a function of the smallest three-dimensional sub-grid volume of the computational volume.

$$\Delta = (\Delta x \Delta y \Delta z)^{\frac{1}{3}} \quad (2.28)$$

### 2.1.3 The cooling source (CS) model

The cooler negatively-buoyant air that grows within the numerical domain and descends to the ground creating the downburst is governed by the forcing cooling source model by Anderson et al. (1992), commonly used in the simulation of downbursts employing subcloud models (Mason et al., 2009; Vermeire et al., 2011a,b; Oreskovic et al., 2018a,b). The space- and time-dependent forcing cooling function $q(x,y,z,t)$ is designed to approximate the structure produced by the full-cloud model simulations (Straka & Anderson, 1993), presented as a product of space and time functions, with the space structure function defined as one cycle of $\cos^2$ of the scaled radial distance from the centre (Anderson et al., 1992), where the scaled radial position $(R)$ of the ellipsoidal region bounded by $R = 1$ (Oreskovic et al., 2018a) is given by the relationship

$$R = \sqrt{\left(\frac{x - x_0}{h_x}\right)^2 + \left(\frac{y - y_0}{h_y}\right)^2 + \left(\frac{z - z_0}{h_z}\right)^2} \quad (2.29)$$

where $(x_0, y_0, z_0)$ is the spatial location of the ellipsoidal CS. $h_x, h_y,$ and $h_z$ are the half-widths of the ellipsoid, and $z_0 = h_c$ (Figure 2.1). The horizontal half-widths of the ellipsoidal CS are equal, $h_x = h_y$ (Anderson et al., 1992).

The space distribution of $q(x,y,z,t)$ in the ellipsoidal CS is described by

$$q(x,y,z,t) = \begin{cases} 
g(t)\cos^2(0.5\pi R) & \text{for } R < 1 \\
0 & \text{for } R > 1 
\end{cases} \quad (2.30)$$

where $R < 1$ is the region inside and $R > 1$ is the region outside the ellipsoid. The space distribution was reported as $\cos^2(\pi R)$ in previous works with scaled radius $R = 0.5$ (Orf & Anderson, 1999; Mason et al., 2009; Vermeire et al., 2011a,b) and $R = 1$ (Oreskovic et al.,
None of these represent the accurate spatial profile of the CS because the cooling rate $q(x,y,z,t)$ is expected to peak at the centre of the CS ($R = 0$) and decrease to zero at the surface ($R = 1$) and outside of the CS. Therefore, Equation (2.30) is the correct formulation, as shown in (Figure 2.2a). It should be noted that the cooling rate equation in the CM1 was implemented correctly in those works, despite the error in the writing of Equation (2.30) in those papers. The function $g(t)$ is the growth of the cooling rate which is set to reach the peak value ($q_{\text{max}}$) after 120 s, remaining constant from 120 s to 720 s, then decreasing until reaching zero cooling rate at 840 s, remaining constant afterward (Figure 2.2b).

$$g(t) = \begin{cases} 
- q_{\text{max}} \cos^2 \left( \frac{\pi (t - 120)}{2(120)} \right) & \text{t} \leq 120 \\
- q_{\text{max}} & 120 < t \leq 720 \\
- q_{\text{max}} \cos^2 \left( \frac{\pi (t - 720)}{2(120)} \right) & 720 < t \leq 840 \\
0 & t > 840 
\end{cases} \quad (2.31)$$

![Figure 2.1: A 3D sketch of the generic forcing cooling source of Anderson et al. (1992).](image)
where \( q(x,y,z,t) = -q_{\text{max}} \) is peak cooling rate and \( q_{\text{max}} \) is its magnitude, given in K/s. For simplicity, the peak cooling rate will be referred to as \( q_{\text{max}} \) in the following chapters. The forcing cooling function will force the temperature field to generate the downburst in the simulations.

Figure 2.2: Typical profile of the cooling rate of the forcing CS by Anderson et al. (1992). (a) Spatial evolution. (b) Temporal profile from 0 s to 840 s.
2.2 The circumferential averaging approach

Due to the enormous data set of velocity vectors at each grid point and time step as the downburst event develops, Orf et al. (2012, 2014) introduced the approach of circumferentially averaging the data obtained from the downburst event simulated using Cloud Model 1 (CM1). Processing the massive 3D velocity data is computationally expensive, and a huge amount of memory is required. As a result, using circumferentially-averaged velocity data reduces computational cost while preserving the flow's most important features: outflow peak speed and corresponding radial location, and some vortices after impinging the ground. The circumferential averaging approach converts the flow velocity \((u, v, w)\) from three-dimensional cartesian coordinates \((x, y, z)\) into a three-dimensional cylindrical coordinate \((r, \theta, z)\), resulting in the velocity vector \((u_r, u_\theta, w)\) where 

\[
u_r = \sqrt{u^2 + v^2}.
\]

Since the flow is mostly linear (no swirling like in tornadoes) the velocity in the azimuthal direction \(u_\theta\) is negligible \((u_\theta = 0)\). The centre of the main downburst is found by identifying the point of divergence of the horizontal wind vectors. Then, at each imposed constant radial distance \(r\) from the impingement and altitude \(z\), the radial \((u_r)\) and vertical \((w)\) wind speeds are spatially averaged around a circumference of the circle of radius \(r\) (Orf et al., 2014). As a result, asymmetric downburst outflow is transformed into symmetric outflow around the circumference of the circle of radius \(r\), and the data are independent of the azimuth angle \(\theta\) \((0 < \theta < 2\pi)\), thereby reducing the three-dimensional data into two-dimensional data set \((r, z)\), with the velocity vector \((u_r, w)\) (Figure 2.3).

Although a real downburst is an asymmetric flow, the simulation of the downburst-producing storm by Orf et al. (2014) demonstrated that the downdraft from the full-storm simulation had an approximately circular base just a few metres \((z < 100 \text{ m})\) above ground level (AGL). Therefore, using the circumferentially-averaged velocity \((u_r, w)\) to analyze the downburst outflow is a successful approach near the ground, which is the region of interest for structural engineers. This method simplifies the analysis and reduces computation time while retaining the peak wind speed and location close to the ground. All the data used in the following chapters were circumferentially averaged for post-processing.
This chapter introduced the general numerical modelling approach employed in this research. The numerical model used is Cloud Model 1 (Bryan, 2002) with a forcing cooling CS based on Anderson et al. (1992) to initiate the downdraft. The turbulence model is solved using the TKE scheme based on Deardorff (1980) as a subgrid-scale. The subsequent chapters will discuss the specific implementations of the model in terms of the computational domain, CS size, shape, location, cooling rate, and the environmental lapse rate (ELR). The following chapter will investigate a scaling approach for downbursts simulated using CM1.

Figure 2.3: Sketch of the r-z coordinates showing the vertical (w) and radial (ur) components of velocity. Velocity components are not drawn to scale.

2.3 Summary

This chapter introduced the general numerical modelling approach employed in this research. The numerical model used is Cloud Model 1 (Bryan, 2002) with a forcing cooling CS based on Anderson et al. (1992) to initiate the downdraft. The turbulence model is solved using the TKE scheme based on Deardorff (1980) as a subgrid-scale. The subsequent chapters will discuss the specific implementations of the model in terms of the computational domain, CS size, shape, location, cooling rate, and the environmental lapse rate (ELR). The following chapter will investigate a scaling approach for downbursts simulated using CM1.
2.4 References


Chapter 3

3 Implementation of the Lundgren et al. (1992) scaling parameters for full-scale cooling source model.

This chapter investigates the application of the Lundgren et al. (1992) scaling parameters – length $R_0$, velocity $V_0$, and time $T_0$ – to simulated downburst events using a subcloud model with a forcing ellipsoidal cooling source (CS) by Anderson et al. (1992). The chapter focuses on simulation cases in which the dimensions of the CS are the same, but with different peak cooling rates.

3.1 Introduction

Downbursts are strong downdrafts that induce an outward burst of damaging winds on or near the ground (Fujita, 1978). They can be classified into wet and dry downbursts. Wet downbursts occur when the downdraft falls with rain, whereas dry downbursts occur when the altitude of the base of the cloud generating the downdraft is sufficiently high to allow the rain to evaporate before the downdraft reaches the ground (Fujita, 1978). Simulated downburst outflows have been scaled by non-dimensionalizing the velocity by the maximum outflow velocity, and the time and position variables by the time and location at which the maximum outflow velocity occurs (Hjelmfelt, 1988; Kim & Hangan, 2007; Lin et al., 2007; Vermeire et al., 2011a). This enabled the comparison of impinging jet (IJ) model data to cooling source (CS) model data (Vermeire et al., 2011a), as well as simulated data to experimental data and downburst field project data. However, this widely used method fails to capture the physics of a transient downburst and forces the data to collapse into a single line, leading investigators to claim that the results agree with project field data (Vermeire et al., 2011a).

A scaling method based on the size of the vortex at the leading edge was proposed by Vermeire et al. (2011a). This scaling method focused on the outflow region, where the maximum radial outflow and primary vortex are identified. This method is more appropriate for comparing IJ models to CS models because it is independent of the inlet conditions (Vermeire et al., 2011a). The scaling method was used on a series of IJ and CS model simulation data, and it allowed the comparison of both models’ outflow near the
ground. The results reinforced that “impulsive driven” IJ models (Selvan & Holmes, 1992) are incapable of accurately modelling downburst outflows near the ground (Vermeire et al., 2011a).

Conversely, Oreskovic et al. (2018a) proposed the use of Lundgren et al. (1992) scaling parameters used in liquid release models — spherical radius ($R_0$), velocity ($V_0$), and time ($T_0$) — to scale the spatial and temporal data obtained from full-scale CS simulations. These parameters were used to define the geometry of the source releasing the downdraft fluid and the non-dimensional density difference ($\Delta\rho/\rho$) between the downdraft density and the ambient density ($\rho$) so that negative buoyancy is created. With $\Delta\rho/\rho = 0.0337$ and a release cylinder of 362 millilitres, stationary downburst experiments were carried out by Graat (2020) and Babaei et al. (2021), and experiments of travelling downbursts in an atmospheric boundary layer were carried out by Jariwala (2021). The velocity profile and magnitude obtained were consistent with field observations such as NIMROD (1985) and JAWS (Hjelmfelt, 1988).

Oreskovic et al. (2018a) used the circumferential averaging approach developed by Orf et al. (2012, 2014) to conduct a parametric study of a downburst simulated using a full-scale CS model. The CS source model by Anderson et al. (1992) was used by Oreskovic et al. (2018a) to carry out several downburst simulations with different peak cooling rates, half-widths, and the height AGL of the CS. The resulting temporal peak radial wind speed profiles of those with a peak cooling rate of -0.08 K/s were non-dimensionalized using the Lundgren et al. (1992) scaling parameters, resulting in the collapse of the curves into a single curve. In addition, the resulting peak non-dimensional wind speed and the corresponding non-dimensional time were comparable to those observed in previous work, showing that these scaling parameters are not solely limited to experimental liquid release models.

However, computing $\Delta\rho/\rho$, which is a critical parameter for determining the scaling time $T_0$, is challenging in CS models due to the spatial and temporal variation of the CS cooling rate. Accurate computation of $\Delta\rho/\rho$ would lead to the correct calculation of the time $T_0$ and the velocity $V_0$, as well as provide an insight into how the buoyancy changes inside the CS.
since it can be quantified by $\Delta p/\rho$ (Spiegel & Veronis, 1960). Oreskovic et al. (2018a) proposed that $\Delta p/\rho$ should be calculated by calculating the spatial average densities over the CS volume. However, this method that spatially averages the densities inside and outside the CS has yet to be developed. This chapter furthers the application of the Lundgren scaling parameters to simulations using the CS by Anderson et al. (1992), by:

- Developing a consistent method for spatially averaging the density inside and outside the CS to calculate $\Delta p/\rho$ (Section 3.5).
- Investigating and scaling the temporal evolution of $\Delta p/\rho$ inside the forcing CS by Anderson et al. (1992) until the downdraft starts (Section 3.7.1).
- Investigating the relationship between $\Delta p/\rho$ and forcing cooling rate inside the CS as the time elapses until the downdraft commences (Section 3.7.2).
- Implementing the Lundgren et al. (1992) scaling parameters to scale the temporal radial speed and the vertical velocity profile of full-scale downburst simulations in which the peak cooling rate of the forcing CS changed while the dimensions of the CS remained constant (Section 3.7.4 and 3.7.5).
- Investigating and scaling the circulation of the strongest vortex ring using the Lundgren et al. (1992) parameters (Section 3.7.6).

3.2 Methodology

The simulations are carried out in Shared Hierarchical Academic Research Computing Network (SHARCNET) using CM1 (Bryan, 2002) with a forcing CS model. The computational domain has a height of 4 km and a square base of a side 9.6 km, creating a volume of $9.6 \text{ km} \times 9.6 \text{ km} \times 4 \text{ km}$. The dimensions of the domain were selected so that domain independence is achieved (Vermeire et al., 2011a). The horizontal mesh grid spacing has the size $\Delta x = \Delta y = 10 \text{ m}$, which gives grid-independent results, with a mean difference in velocity of 0.09% when compared with a very refined mesh having $\Delta x = 6 \text{ m}$ (Oreskovic, 2016). For the vertical mesh, a mesh refinement was applied by using a stretching mesh based on Wilhelmson and Chen (1982). The first grid point above the ground is at $\Delta z = 1 \text{ m}$, stretching to $\Delta z = 50 \text{ m}$ at the top of the domain giving 160 horizontal planes. This generates a total of 147,456,000 grid points for the mesh in the full domain.
The boundary conditions are chosen so that the downburst is simulated in conditions like those observed in actual downburst events. The lateral sides of the domain are treated as open-radiative surfaces to allow the flow to enter and exit the domain. Similar to previous work (Mason et al., 2009; Vermeire et al., 2011a,b; Oreskovic et al., 2018a,b), the bottom surface is treated as a semi-slip surface with the surface roughness set to $z_0 = 0.10$ m, equivalent to short-crop terrain (Vermeire et al., 2011a) and similar to that used by Oreskovic et al. (2018a). The heat fluxes between the bottom surface and the air are not included since there is no difference in temperature. The top surface of the domain is set as a free-slip condition. Previous studies (Srivastava 1985, 1987; Proctor, 1988; Hjelmfelt et al., 1989) showed that stronger downdrafts are produced when the environmental lapse rate equals the dry adiabatic lapse rate (Srivastava 1985, 1987; Proctor, 1988; Hjelmfelt et al., 1989). Therefore, to produce strong downbursts, a dry adiabatic lapse rate ($\Gamma = 9.8$ K/km) is applied in a quiescent atmosphere with a constant and uniform ground surface temperature of 300 K. A time step of $\Delta t = 0.05$ s with 10 acoustic sub-steps was used to maintain computational stability while achieving time-step independence (Oreskovic, 2016), and all the simulations were run for 10 min, enough time to allow for the decay of the vortices in the simulated downburst outflows. Each simulation took approximately 4 hours in real-time.

### 3.3 Numerical simulation data

The numerical simulations are carried out in SHARCNET using the latest version (cm1r19.10) of the cloud model CM1 (Bryan, 2002; Bryan & Fritsch, 2002). The simulation data are named in the form $q_{\text{max}}$$_h$$_x$$_h$$_z$$_h$$_c$, where $q_{\text{max}}$ is the peak cooling rate of the forcing CS, $h_x$ (equal to $h_y$) and $h_z$ are the horizontal and vertical half-widths of the ellipsoidal CS by Anderson et al. (1992), as shown in Figure 3.1, and $h_c$ is the height at which the centre of the CS is located. The dimensions of the forcing CS ($h_x$, $h_y$, $h_z$), which are the same as the baseline simulation in previous works (Anderson et al., 1992; Vermeire et al., 2011a, Oreskovic et al., 2018a), are maintained constant at $h_x = h_y = 1200$ m, $h_z = 1800$ m, and $h_c = 2000$ m, while the peak cooling rate ($q_{\text{max}}$) is varied from the baseline case $q_{\text{max}} = 0.08$ K/s (Vermeire et al., 2011a, Oreskovic et al., 2018a). Table 3.1 lists the simulation data that will be analyzed and discussed in this chapter.
Table 3.1: Simulations conducted in CM1 at peak cooling rate of the CS.

<table>
<thead>
<tr>
<th>Simulations in CM1</th>
<th>$q_{\text{max}}$ (K/s)</th>
<th>$h_x, h_y$ (m)</th>
<th>$h_z$ (m)</th>
<th>$h_c$ (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>004-1200-1800-2000</td>
<td>0.04</td>
<td>1200</td>
<td>1800</td>
<td>2000</td>
</tr>
<tr>
<td>006-1200-1800-2000</td>
<td>0.06</td>
<td>1200</td>
<td>1800</td>
<td>2000</td>
</tr>
<tr>
<td>008-1200-1800-2000</td>
<td>0.08</td>
<td>1200</td>
<td>1800</td>
<td>2000</td>
</tr>
<tr>
<td>010-1200-1800-2000</td>
<td>0.10</td>
<td>1200</td>
<td>1800</td>
<td>2000</td>
</tr>
</tbody>
</table>

3.4 Lundgren et al. (1992) scaling parameters

Lundgren et al. (1992) proposed a scaling law that allows liquid release experiments to be compared to one another as well as to numerical models. It also aids in the comparison of simulated downburst events to real-world downburst events. The scaling law, which was developed from simple mathematical modeling of idealized downbursts, has proven to be
useful in laboratory liquid release experiments (Babaei et al., 2020; Graat, 2020; Jariwala, 2021). These are the parameters that comprise the scaling law by Lundgren et al. (1992): the characteristic length $R_0$, the characteristic time $T_0$, and the velocity scale $V_0$. All lengths are made dimensionless by the characteristic length $R_0$, which is defined as the equivalent spherical radius.

$$R_0 = \left( \frac{3Q}{4\pi} \right)^{\frac{1}{3}}$$  \hspace{1cm} (3.1)

where $Q$ is typically defined as the volume of the source generating the downburst. In the current simulation, $Q$ is the volume of the ellipsoidal CS in Figure 3.1.

$$Q = \frac{4}{3} \pi h_x h_y h_z$$  \hspace{1cm} (3.2)

All velocity variables are made dimensionless by the velocity scale $V_0$, given by

$$V_0 = \frac{R_0}{T_0}$$  \hspace{1cm} (3.3)

The time variable is made dimensionless by the characteristic time $T_0$, formulated from the governing equations of motion by assuming the flow to be incompressible and inviscid, with the density difference ($\Delta \rho$) sufficiently small that the Boussinesq approximation (Spiegel & Veronis, 1960; Turner, 1973) can be used. Applying these assumptions, the equations of motion can be written in the form:

$$\nabla \cdot \vec{V} = 0$$  \hspace{1cm} (3.4)

$$\frac{d\vec{V}}{dt} = -\frac{\nabla p}{\rho} - g \frac{\Delta \rho}{\rho}$$  \hspace{1cm} (3.5)

where $\vec{V}$ is the velocity vector, $p$ is the total pressure, $\Delta \rho/\rho$ is the nondimensional density difference due to the microphysics inside the downburst ($\Delta \rho/\rho = 0$ outside the downburst parcel), and $\rho$ is the ambient density. The density difference is given by $\Delta \rho = \rho_0 - \rho$, where
\( \rho_0 \) is the density inside the downburst parcel. Non-dimensionalizing Equation (3.4) and (3.5) by \( x^* = x/R_0 \), \( t^* = t/T_0 \), \( V^* = V/V_0 \), and \( p^* = p/(\rho V_0^2) \) gives

\[
\nabla^* \cdot V^* = 0
\]

\( \text{(3.6)} \)

\[
\frac{dV^*}{dt^*} = -V^* p^* - g \frac{T_0^2 \Delta \rho}{R_0 \rho} \frac{\vec{k}}{k}
\]

\( \text{(3.7)} \)

For unit order of magnitude in Equation (3.7), time scale \( T_0 \) is defined as

\[
T_0 = \left( \frac{R_0 \rho}{g \Delta \rho} \right)^{\frac{1}{2}}
\]

\( \text{(3.8)} \)

Two important dimensionless numbers can be determined with the scaling variables: the Reynolds number (Re) and the densimetric Froude number (Fr) (Turner, 1973) for the Boussinesq approximation.

\[
Re = \frac{V_0 R_0}{\nu}
\]

\( \text{(3.9)} \)

\[
Fr = \frac{V_0}{\sqrt{R_0 g \frac{\Delta \rho}{\rho}}}
\]

\( \text{(3.10)} \)

where \( \nu \) is the kinematic viscosity. Equations (3.7) and (3.8) imply that the Froude number must be of unit order to balance the buoyancy and inertial forces.

\[
Fr \sim 1
\]

\( \text{(3.11)} \)

A physical interpretation of \( \Delta \rho/\rho \) can be obtained from Equations (3.10) and (3.11) which gives

\[
\frac{\Delta \rho}{\rho} \sim \frac{V_0^2}{g R_0}
\]

\( \text{(3.12)} \)
According to Equation (3.12), the non-dimensional density difference can be interpreted as the ratio of kinetic energy to potential energy, or as the fraction of the downdraft's potential energy that is converted into kinetic energy.

Equations (3.1), (3.3), and (3.8) show that the scaling parameters $R_0$, $T_0$, and $V_0$, are only dependent on the volume of the source $Q$ and the non-dimensional density difference $\Delta \rho/\rho$. This simple finding has been an important factor considered by researchers (Lundgren et al., 1992; Alahyari & Longmire, 1994, 1995; Yao & Lundgren, 1996; Babaei, 2018; Graat, 2020; Babaei et al., 2021; Jariwala, 2021) in carrying out the liquid release experiments because they imply that a source of certain geometry and liquids of different densities are needed to simulate a downburst (Figure 3.2). It is worth noting that $\Delta \rho/\rho$ can be easily computed in liquid release models because the densities of the fluids used are known and considered constant, and the boundary between the two liquids is well-defined with a step change in density between them. However, in CS models, ambient density and downburst parcel density vary spatially and temporally, requiring a specific mathematical approach to compute $\Delta \rho/\rho$. This approach is further discussed in the following section.

![Figure 3.2: Schematic showing a basic liquid release experiment.](image)

### 3.5 Mathematical approach to the calculation of $\Delta \rho/\rho$

The non-dimensional density difference at a single time step $t_i$ is computed by

$$
\frac{\Delta \rho}{\rho}(t_i) = \frac{\bar{\rho}_{\text{in}}(t_i) - \bar{\rho}_{\text{out}}(t_i)}{\bar{\rho}_{\text{out}}(t_i)}
$$

(3.13)
where $\bar{\rho}_{\text{out}}(t_i)$ and $\bar{\rho}_{\text{in}}(t_i)$ are the spatial average (mean) densities outside and inside the forcing cooling source at a single time step $t_i$ respectively.

3.5.1 Mathematical procedure to compute the spatial average density inside the forcing cooling source.

The spatial average density inside the CS at a single time step $t_i$ can be calculated by using the average value formula (Marsden & Tromba, 2012):

$$
\bar{\rho}_{\text{in}}(t_i) = \frac{\iiint_{Q_{\text{in}}} \rho(x, y, z, t_i) \, dx \, dy \, dz}{Q_{\text{in}}}
$$

where $\rho(x, y, z, t_i)$ and $Q_{\text{in}}$ represent the density and volume inside the forcing cooling source (CS), respectively. $Q_{\text{in}}$ is given by Equation (3.2). The integral in (3.14) is difficult to evaluate numerically and analytically because density is a function of space $(x, y, z)$ and time $t_i$. Therefore, the circumferentially-averaged density, $\rho = \rho(r, z)$ is used to compute the spatial average density inside the CS at each time step. Using cylindrical coordinates,

$$
\bar{\rho}_{\text{in}}(t_i) = \frac{\iiint_{Q_{\text{in}}} \rho(r, \theta, z, t_i) \, rdr \, d\theta \, dz}{Q_{\text{in}}}
$$

Due to the symmetry of the forcing CS, the circumferentially-averaged density is independent of the azimuthal angle $\theta$, as discussed in Chapter 2.

$$
\rho(r, \theta, z, t_i) \approx \rho(r, z, t_i), \quad \text{for } 0 \leq \theta \leq 2\pi
$$

Considering (3.16), Equation (3.15) can be simplified further to

$$
\bar{\rho}_{\text{in}}(t_i) = \frac{2\pi}{Q_{\text{in}}} \int_A \rho(r, z, t_i) \, rdr \, dz
$$

where $A$ denotes the cross-section area in the $r$-$z$ plane (Figure 3.3). Equation (3.17) can be solved numerically using MATLAB to obtain the spatial averaged density inside the CS.
3.5.2 Mathematical procedure to compute the spatial average density outside the forcing CS.

The spatial average density outside the CS at each time step \( t_i \) is also computed by the average value formula (Marsden & Tromba, 2012):

\[ \bar{\rho}_{\text{out}}(t_i) = \frac{\iiint_{Q_{\text{out}}} \rho(x, y, z, t_i) \, dx \, dy \, dz}{Q_{\text{out}}} \]  

(3.18)

where \( \rho(x, y, z, t_i) \) and \( Q_{\text{out}} \) represent the density and volume outside the forcing CS. For simplicity in using cylindrical coordinates, \( Q_{\text{out}} \) is assumed to be the volume of the cylinder of maximum radial distance \( (R_{\text{max}} = 9.6 \, \text{km}) \) and height \( (H_{\text{max}} = 4 \, \text{km}) \) that can be enclosed inside the computational domain (Figure 3.4).

\[ Q_{\text{out}} = \pi R_{\text{max}}^2 H_{\text{max}} - \frac{4}{3} \pi h_x h_y h_z \]  

(3.19)

Similar to the previous section, Equation (3.18) can be reduced to
\[ \bar{\rho}_{\text{out}}(t_i) = \frac{2\pi}{Q_{\text{out}}} \int_A \rho(r, z, t_i) r \, dr \, dz \]  

(3.20)

where \( A \) denotes the cross-section area outside the forcing CS, as seen in **Figure 3.4**.

![Figure 3.4: Representation of the cross-section area \( A \) inside the ellipsoidal CS.](image)

**3.6 Computation of **\( \Delta \rho / \rho \) **and the scaling parameters** \( R_0, T_0, \) **and** \( V_0. **

The computation of the scaling parameters involves solving \( \Delta \rho / \rho \) from Equations (3.17) and (3.20). However, proper boundary conditions or limits of integration need to be defined. Based on the size of the ellipsoidal cooling source, the boundary conditions inside is

\[ 0 \leq r \leq h_x \quad \text{and} \quad h_c - h_z \leq z \leq h_c + h_z \]  

(3.21)

However, this results in scaling parameters that do not collapse the data into a single curve, which is unexpected given that the Lundgren et al. (1992) scaling parameters work for cooling source simulations (Oreskovic et al., 2018a). Therefore, trial-and-error is used to
determine the boundary conditions that aid in the correct computation of the scaling parameters. This differs from the approach taken by Oreskovic et al. (2018a), who arbitrarily used a potential temperature $\theta = 299$ K as a reference, with $\theta < 299$ K representing the region inside the CS and $\theta > 299$ K representing the region outside. Different peak cooling rates will result in different potential temperatures, making it difficult to choose a reference potential temperature to define the integration region that would be suitable for all cases. The trial-and-error method adds a scaling value $\beta$ so that the boundary conditions inside become

$$0 \leq r \leq \beta h_x, \quad h_c - \beta h_z \leq z \leq h_c + \beta h_z$$  \hspace{1cm} (3.22)

The volume inside and the volume outside the forcing CS are now a function of $\beta$.

$$Q_{in} = Q_{in}(\beta) = \beta^3 \frac{4}{3} \pi h_x h_y h_z$$  \hspace{1cm} (3.23)

$$Q_{out} = Q_{out}(\beta) = \pi R_{max}^2 H_{max} - \beta^3 \frac{4}{3} \pi h_x h_y h_z$$  \hspace{1cm} (3.24)

Through trial-and-error, the scaling parameters that collapse the curves into a single unique curve (discussed later) are obtained when $\Delta \rho/\rho$ is calculated with $\beta = 0.622$. This value appears to have a physical meaning because the downdraft has a radius of approximately 740 m (Figure 3.5a and b), equivalent to 0.622 $h_x$, found to be constant in all simulations listed in Table 3.1. This implies that to successfully compute the scaling parameters ($R_0$, $T_0$, $V_0$), $\Delta \rho/\rho$ is determined by integrating in a region inside the CS with a radius equal to the radius of the downdraft just before it impinges on the ground. Note that Figure 3.5a shows that the radial distance of 0.622$h_x$ is equivalent to the potential temperature of 298 K, which is less than the 299 K arbitrarily chosen by Oreskovic et al. (2018a). Therefore, this approach resembles the one by Oreskovic et al. (2018b), except that the potential temperature is not arbitrarily chosen, rather obtained due to the scaling value of $\beta$. The calculated scaling parameters $R_0$, $T_0$, and $V_0$, are presented in Table 3.2, where the $\Delta \rho/\rho$ presented are the maximum values that occur at $t = 210$ s (Discussed later in section 3.7.3).
Table 3.2: Summary of Lundgren et al. (1992) scaling parameters

<table>
<thead>
<tr>
<th>$q_{\text{max}}$ (K/s)</th>
<th>$\Delta \rho/\rho$</th>
<th>$R_0$ (m)</th>
<th>$T_0$ (s)</th>
<th>$V_0$ (m/s)</th>
<th>$Re$</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.10</td>
<td>0.0215</td>
<td>1373</td>
<td>80.70</td>
<td>17.02</td>
<td>$1.57 \times 10^9$</td>
</tr>
<tr>
<td>0.08</td>
<td>0.0192</td>
<td>1373</td>
<td>85.40</td>
<td>16.08</td>
<td>$1.48 \times 10^9$</td>
</tr>
<tr>
<td>0.06</td>
<td>0.0160</td>
<td>1373</td>
<td>93.55</td>
<td>14.68</td>
<td>$1.35 \times 10^9$</td>
</tr>
<tr>
<td>0.04</td>
<td>0.0125</td>
<td>1373</td>
<td>105.84</td>
<td>12.97</td>
<td>$1.20 \times 10^9$</td>
</tr>
</tbody>
</table>

Figure 3.5: Contours of potential temperature for $q_{\text{max}} = 0.08$ K/s (a) showing the region of width $0.622 h_x$ used to compute $\Delta \rho/\rho$, which is equivalent to the radius of the downflow before impinging the ground, as shown in (b).
It should be noted that the spatially-averaged $\Delta \rho/\rho$ obtained for the baseline simulation 008-1200-1800-2000 is equal to 0.0192, which was previously overestimated $\Delta \rho/\rho = 0.040$ (Oreskovic et al., 2018a). This overestimation was due to the use of the arithmetic mean to calculate mean density inside and outside the CS (Oreskovic et al., 2018a). This method is incorrect because the density varies with time and position. The average integral approach used in this chapter is more suitable for estimating the spatial average density inside and outside the microburst parcel.

### 3.6.1 An estimate of the percentage error associated with the spatial averaging density method.

The percentage error was calculated using the density at the start of the simulation ($t = 0$ s). At $t = 0$ s, the density $\rho = 1.1614$ kg/m$^3$ is uniform throughout the entire domain. This means that at $t = 0$ s, the average density inside and outside the microburst parcel is the same, 1.1614 kg/m$^3$. Spatially averaging the density for the simulation 008-1200-1800-2000 at $t = 0$ s using the approach discussed in the previous section, yields slightly different values: 1.1628 kg/m$^3$ inside and 1.1607 kg/m$^3$ outside the forcing CS. Table 3.3 summarizes the results obtained. The percentage difference between the use of the numerical approach to evaluate the spatially average density inside and outside is 0.12% and 0.06% respectively, which were obtained using Equation (3.25). The percentage error associated with the spatially averaging density approach is so small that it would not affect the data normalization.

$$\text{Percentage difference} = \frac{|\bar{\rho} - \rho|}{\frac{\bar{\rho} + \rho}{2}} \times 100\% \quad (3.25)$$

<table>
<thead>
<tr>
<th>Density (kg/m$^3$)</th>
<th>Inside the forcing CS</th>
<th>Outside the forcing CS</th>
</tr>
</thead>
<tbody>
<tr>
<td>At $t = 0$ s ($\rho$)</td>
<td>1.1614</td>
<td>1.1614</td>
</tr>
<tr>
<td>Spatially averaged at $t = 0$ s ($\bar{\rho}$)</td>
<td>1.1628</td>
<td>1.1607</td>
</tr>
<tr>
<td>Percentage difference (%)</td>
<td>0.12</td>
<td>0.06</td>
</tr>
</tbody>
</table>

Table 3.3: Percentage difference associated with the numerical integral approach
3.7 Results and discussion

This section presents and analyzes the results of simulations conducted with CM1 and a forcing CS. The computation of the scaling parameters is presented, followed by their application. Vortex identification is also discussed.

3.7.1 Temporal evolution of the non-dimensional density difference ($\Delta \rho / \rho$) for the cooling source by Anderson et al. (1992).

The time history of the spatially-averaged non-dimensional density difference ($\Delta \rho / \rho$) inside the forcing CS for each simulation conducted is presented in Figure 3.6a, which shows the nonlinear increase of $\Delta \rho / \rho$ with time. As the cooling rate of the CS increases (Figure 3.6b), the non-dimensional density difference $\Delta \rho / \rho$ inside the forcing CS increases until reaching a peak value (Figure 3.6). This indicates that as the cooling rate of the CS increases, a fraction of the potential energy is converted into kinetic energy, but the fraction is so small that vertical motion has not yet been detected. The vertical motion of the downdraft is first detected at $t = 180$ s while $\Delta \rho / \rho$ continues to increase, reaching its peak value at $t = 210$ s (Figure 3.6a). This means that a greater fraction of the potential energy of the imposed forcing CS must be converted into the kinetic velocity to detect vertical motion. The peak $\Delta \rho / \rho$ values, listed in Table 3.2, were used to determine the Lundgren et al. (1992) scaling parameter $T_0$, which were employed to normalize the radial wind speed data (to be discussed in section 3.7.3).

An attempt to normalize the data in Figure 3.6 is carried out by dividing $\Delta \rho / \rho$ by the peak $\Delta \rho / \rho$ value, and time by the scaling time $T_0$, with the results shown in Figure 3.7a. By observation, it can be concluded that the scaling works well for $q_{max} = 0.08$ K/s and $q_{max} = 0.10$ K/s, due to the collapse of the data into a single. The self-similarity (collapse) of the curves is quantified using percentage difference (PD) analysis. The case $q_{max} = 0.08$ K/s is chosen as the reference case and the percentage differences between the other cases with the reference case are calculated. Figure 3.7b confirms that there is a similarity between case $q_{max} = 0.08$ K/s and $q_{max} = 0.10$ K/s for $1.0 < t/T_0 < 2.7$ within 10% percentage difference error (the black dashed line), which decreases further and is less than 5% for
$1.25 < t/T_0 < 2.7$. In addition, the collapse with $q_{\text{max}} = 0.06 \, \text{K/s}$ is considered good for $1.25 < t/T_0 < 2.7$ within 10% difference percentage error (Figure 3.7b), but poor for $t/T_0 < 1.0$. The case $q_{\text{max}} = 0.04 \, \text{K/s}$ is poor for any $t/T_0$. Despite the poor scaling results for $q_{\text{max}} = 0.04 \, \text{K/s}$, Figure 3.7a shows that the increase of the cooling rate and $\Delta \rho/\rho$ before the downdraft starts is similar regardless of the peak cooling rate of the forcing cooling source.

**Figure 3.6:** Time history series until the downdraft starts for the four peak cooling rates cases. (a) Spatially-averaged non-dimensional density difference $\Delta \rho/\rho$. (b) Cooling rate at the centre of the CS, $q(0,0,z,t)$. 
3.7.2 Investigation of the variation of the cooling rate with the non-dimensional density difference ($\Delta \rho / \rho$) at the centre of the cooling source.

The cooling rate at the centre of the imposed forced cooling source ($-q(0,0,z,t)$) increases with time until it reaches its peak $q_{\text{max}}$ at $t = 120$ s, due to the cooling source function used, which was discussed in detail in Chapter 2, including the typical cooling source temporal profile. Since the final simulation time is 600 s, $q(0,0,z,t)$ remains constant after reaching
its peak value. As the cooling rate increases, so does the non-dimensional density difference $\Delta \rho/\rho$. Figure 3.8 demonstrates the relationship between the cooling rate at the centre of the CS and the non-dimensional density difference $\Delta \rho/\rho$, with data points obtained at $t = 0, 30, 60, 90, 120, 150, 180, 210, 240$ s. As shown in Figure 3.7 and Figure 3.8, a similar curve shape is obtained regardless of the peak cooling rate set to the forcing cooling source. This implies that a normalized plot of Figure 3.8 can be obtained, in which all the curves would collapse into a single curve since the variation of the cooling rate is the same.

Figure 3.8: Cooling rate $-q(0,0,z,t)$ versus $\Delta \rho/\rho$ inside the downburst parcel at $t = 0, 30, 60, 90, 120, 150, 180, 210, 240$ s.

The variables $-q(0,0,z,t)$ and $\Delta \rho/\rho$ were first normalized by dividing by their respective maximum values $q_{\text{max}}$ and $(\Delta \rho/\rho)_{\text{max}}$, which is a widely accepted normalization method (Mason et al., 2009). Figure 3.9a shows that when the curves are normalized using the method described, they do not collapse very well. A successful normalization was obtained by including the variable time, resulting in $\Delta \rho/\rho$ normalized by dividing not only by the maximum $\Delta \rho/\rho$ value but also multiplied by $t/t_{\text{max}}$, where $t_{\text{max}}$ is the time when the peak
cooling rate of the cooling source is reached, $t_{\text{max}} = 120$ s. Figure 3.9b shows the normalization from the second approach. When compared to the normalized plot in Figure 3.9a, there is a significant improvement since the curves can be considered similar within 10% of percentage difference (PD) error as shown in Figure 3.10, where the PD is estimated with respect to the reference case ($q_{\text{max}} = 0.08$ K/s).

Figure 3.9: Normalization of the cooling rate versus $\Delta \rho/\rho$. (a) Using $q_{\text{max}}$ and $(\Delta \rho/\rho)_{\text{max}}$ only. (b) Using $q_{\text{max}}$ and $(\Delta \rho/\rho)_{\text{max}}$, including the normalization of the variable time by the time that peak cooling rate is achieved, $t_{\text{max}} = 120$ s.
3.7.3 Normalization of the temporal peak radial wind speed by the Lundgren et al. (1992) scaling parameters $V_0$ and $T_0$

Figure 3.11 presents the time history of the peak radial wind speed of the simulations listed in Table 3.1. When the peak cooling rate of the forcing CS is increased to 0.10 K/s, the peak outflow radial wind speed ($u_{r,\text{max}}$) increases significantly, reaching a value greater than 50 m/s. However, decreasing the peak cooling rate to 0.04 K/s decreased $u_{r,\text{max}}$ to 39 m/s. Oreskovic et al. (2018a) observed the same effects when investigating the effects of the peak cooking rate ($q_{\text{max}}$) on the peak radial wind speed. Normalizing Figure 3.11 by the determined scaling variables in Table 3.2, the curves collapse into a single curve, with the percentage deviation from the mean (RMS (%)) less than 10% (equivalent to RMS(%)/100 < 0.1) (Figure 3.12). This means that the baseline simulations with different peak cooling rates have a similar solution, which can be combined into a singular curve relating the non-dimensional peak radial speed $u_{r,\text{max}}/V_0$ to the non-dimensional time $t/T_0$. (Figure 3.12). The non-dimensional peak radial wind speed $u_{r,\text{max}}/V_0 = 3.25$ occurs at the non-dimensional time $t/T_0 = 4.0$. 

Figure 3.10: The percentage difference between the reference case ($q_{\text{max}} = 0.08$ K/s) and other cases.
Figure 3.11: Temporal variation of the peak radial wind speed for the CS simulations with different peak cooling rates.

Figure 3.12: Normalized plot of the temporal variation of the peak radial wind speed by Lundgren et al. (1992) scaling parameter $V_0$ and $T_0$. 
3.7.4 Normalization of the vertical profile of the radial wind speed by the Lundgren et al. (1992) scaling parameters \( V_0 \) and \( R_0 \)

Since the vertical profile shape depends on the time and the radial distance from the centre, the analyses were carried out at a specific time and radial location of interest. Figure 3.13 shows the radial evolution of the radial wind speed at the time the peak non-dimensional radial velocity \( u_{r,\text{max}}/V_0 \) occurs, \( t/T_0 = 4.0 \), with focus on the radial location \( r/R_0 = 1.05 \) (Figure 3.13a), \( r/R_0 = 1.16 \) (Figure 3.13b), \( r/R_0 = 1.23 \) (Figure 3.13c), and the peak radial wind speed location \( r/R_0 = 1.38 \) (Figure 3.13d). It can be observed that increasing the peak cooling rate of the CS increases the magnitude of the radial wind speed, which agrees with previous work (Mason et al., 2009; Oreskovic et al., 2018a). However, the profile shape remains approximately the same at each radial location regardless of the peak cooling rate.

A typical downburst vertical velocity profile shape (Lin, 2010) is observed at the radial location less than \( r/R_0 = 1.38 \), which is the radial location where the peak \( u_{r,\text{max}}/V_0 \) occurs at \( t/T_0 = 4 \) (Figure 3.13a, b). However, approaching \( r/R_0 = 1.38 \), the presence of the vortex ring near the ground starts distorting the vertical profile shape near the ground due to radial speed in the opposite direction, as shown in Figure 3.13c and Figure 3.13d. Figure 3.14 presents the normalized radial wind speed profile of the plots in Figure 3.13. The vertical profile curves collapse into a single curve with a percentage root-mean-squared less than 10% as seen in Figure 3.15, demonstrating the usefulness of the Lundgren et al. (1992) scaling parameters for simulation of downburst events using CS. The near-ground peak radial wind speed at \( r/R_0 = 1.05 \), \( r/R_0 = 1.16 \), \( r/R_0 = 1.23 \), and \( r/R_0 = 1.38 \) are observed at the non-dimensional height \( z/R_0 = 0.009 \), \( z/R_0 = 0.011 \), \( z/R_0 = 0.036 \), and \( z/R_0 = 0.095 \).
Figure 3.13: Radial wind speed vertical profile at $t/T_0 = 4.0$ and a) $r/R_0 = 1.05$, b) $r/R_0 = 1.16$, c) $r/R_0 = 1.23$, and d) $r/R_0 = 1.38$. 
Figure 3.14: Normalized vertical radial wind speed profile by the Lundgren et al. (1992) scaling parameters $R_0$ and $T_0$ at $t/T_0 = 4.0$ and a) $r/R_0 = 1.05$, b) $r/R_0 = 1.16$, c) $r/R_0 = 1.23$, d) $r/R_0 = 1.38$.

Figure 3.15: Root-mean-squared percentage of the normalized vertical radial wind speed profile at $t/T_0 = 4.0$ and non-dimensional radial locations analyzed.
The vertical profiles at $t/T_0 = 4.0$ and radial locations analyzed above are compared with liquid release experiments (Graat, 2020; Jariwala, 2021) and cooling source simulation (Oreskovic et al., 2018a) in Figure 3.16, where DB US and DB DS represent the non-dimensionalized peak horizontal speed profile of the upstream and downstream regions, respectively, of the travelling downburst experiments by Jariwala (2021). There is a similar pattern in the shape of the profiles (Figure 3.16), with the non-dimensional radial wind speed ($u_r/V_0$) starting at zero at the bottom surface and increasing as the non-dimensional height ($z/R_0$) increases until reaching a peak $u_r/V_0$ at a certain $z/R_0$, then decreasing until nearly zero and remaining roughly steady. The best profile similarity is observed between the current simulations at $r/R_0 = 1.05$ and the vertical radial wind profile in the CS simulation by Oreskovic et al. (2018b) at the time and location the peak radial wind speed occurs (Figure 3.16). In addition, the $z/R_0$ corresponding to the peak $u_r/V_0$ are approximately equal to $z/R_0 = 0.010$. However, the peak $u_r/V_0$ magnitude are different, with $u_r/V_0 = 1.80$ for CS_008_1200_1333 (Oreskovic et al., 2018a) and $u_r/V_0 = 2.50$ at $r/R_0 = 1.05$ for current CS simulations. This difference is probably due to the different $\Delta \rho/\rho$ value, $\Delta \rho/\rho = 0.040$ (Oreskovic et al., 2018b), used in the calculation of the scaling variables ($T_0, V_0$) since a high $\Delta \rho/\rho$ value decreases $u_r/V_0$ as seen in the relationship (3.27) obtained from Equations (3.10) and (3.11).

$$\frac{u_r}{V_0} \propto \left(\frac{\Delta \rho}{\rho}\right)^{-1/2}$$ (3.26)

It is also observed that there is a considerable difference in the peak $u_r/V_0$ and the corresponding height between the CS simulations and the liquid release experiments (Graat, 2020; Jariwala, 2021) (Figure 3.16). This difference can be justified by the low Reynolds number of those experiments, $\text{Re} = 4565$ (Graat, 2020; Jariwala, 2021), compared to the minimum $\text{Re} = 1.20 \times 10^9$ in current CS simulations. In addition, the experiments by Jariwala (2021) were travelling downbursts in the atmospheric boundary layer, different from the quiescent environment used in the CS simulations. Those profiles (Jariwala, 2021) were included in Figure 3.16 for comparison with the present study regarding the shape profile, and not the peak wind speed.
Identification and quantification of the vorticity at the location of peak radial wind speed.

This section analyses the outflow behaviour and structure, focusing on the detection of vortex rings in the outflow after the impingement. The Q criterion (Chen et al., 2015) was employed to detect the vortex rings near the ground. The Q criterion (Chen et al., 2015) measures the difference between the rate-of-rotation tensor ($\Omega$) for pure rotational motion and the rate-of-strain tensor ($S$) for pure irrotational motion.

$$Q = \frac{1}{2} (\|\Omega\|^2 - \|S\|^2)$$  \hspace{1cm} (3.27)

where

$$\Omega = \frac{1}{2} (\nabla U - \nabla U^T)$$  \hspace{1cm} (3.28)

Figure 3.16: Comparison of the vertical profile of the radial wind speed of the present simulated downburst with previous work at the time and radial location of the peak radial wind speed.
and

\[ S = \frac{1}{2} (\nabla U + (\nabla U)^T) \]  

(3.29)

where \( \nabla U \) is the full local velocity gradient tensor and \( \nabla U^T \) is its transpose. For a 2D velocity gradient tensor in the plane \((r, z)\), Equation (3.27) can be simplified to

\[ Q = -\left( \frac{\partial u_r}{\partial z} \frac{\partial u_z}{\partial r} - \frac{\partial u_r}{\partial r} \frac{\partial u_z}{\partial z} \right) - \frac{1}{2} \left( \frac{\partial u_r}{\partial r} + \frac{\partial u_z}{\partial z} \right)^2 \]  

(3.30)

where \( u_z = w \). A positive Q-value indicates that there is an excess of rotation rate relative to strain rate (Chen et al., 2015), and this is the location of a vortex. It should be noted that, although the Q criterion is capable of efficiently detecting vortices, it is more accurate in identifying strong vortices than weak ones (Chen et al., 2015). As a result, some weak vortices (secondary vortices) may go undetected. The Q criterion is applied to identify the vortices for the four cases analyzed, at the time the non-dimensional peak wind speed occurs, \( t/T_0 = 4.0 \). The Q-value is non-dimensionalized by \( (V_0/R_0)^2 \) since Q has units of \( 1/s^2 \). Figure 3.17 shows the vortex rings identified, where the collapse of the data onto a single curve obtained in the scaling of the temporal and vertical radial speed profile in the previous section is also reflected in this plot since the non-dimensional \( R_0^2 Q/V_0^2 \) field of the four cases is approximately the same. It is also observed the primary vortex rings at \( r/R_0 = 1.23 \) and \( r/R_0 = 1.38 \), in Figure 3.17, clarifying the distortion in the vertical profile shape obtained in the previous section at those locations (Figure 3.14c and d).

Figure 3.18 shows the temporal propagation of the primary vortex ring in the outflow of the baseline case (\( q_{\text{max}} = 0.08 \text{ K/s} \)) as detected by the Q criterion at \( t/T_0 = 3.51, 3.86, 4.51, \) and 4.68. The vortex rings develop behind the leading edge of the outflow and are attached to the ground (\( t/T_0 = 3.51 \)) as they form. The rings start stretching and detaching from the ground as time elapses. After some time (\( t/T_0 = 4.68 \)), the strongest vortex core (primary vortex) is located above the ground before it dissipates. The same vortex behaviour is observed in other cases as the field would collapse and be the same at the same non-dimensional time \( t/T_0 \) as shown in Figure 3.17. In addition, since roughness and environmental conditions are the same, the same behaviour is expected as discussed by
Vermeire et al. (2011a). Therefore, not shown here. The vorticity of the vortex rings is negative (clockwise direction) near the ground (Figure 3.17 and Figure 3.18) due to the ground roughness. This negative vorticity also was observed in simulations that included precipitation, which revealed a negative stretching ring vortex that expanded behind the leading edge (Proctor, 1988). However, there is a secondary vortex ring oriented counterclockwise centred at \( r/R_0 = 1.23 \) and \( z/R_0 = 0.20 \) at \( t/T_0 = 4.0 \) as seen in Figure 3.17, which develops alongside the negative vortex (primary vortex), located above it at \( t/T_0 = 3.51, 3.85 \) (Figure 3.18), and later located below it, \( t/T_0 = 4.68 \) (Figure 3.18). This secondary vortex is not well detected by the Q criterion since it is weak.

Figure 3.17: Identification of the vortex rings for the four peak cooling rate cases at \( t/T_0 = 4.0 \).

The strength of the vortex rings can be quantified by the value of its circulation \( C(t) \), which is calculated by integrating the velocity field along the closed contour line \( l(t) \) that encloses the region with the largest vortex ring or the region with the highest \( Q \)-value, oriented clockwise, using Equation (3.31) (Marsden & Tromba, 2012), where \( \vec{V} = (u_r, w) \). Both
circulation and the contour line are time dependent because the downburst outflows are unsteady, and the vortex ring size changes with time due to stretching caused by the ground roughness.

\[ C(t) = \oint_{l(t)} \vec{V} \cdot d\vec{l} \]  

(3.31)
Figure 3.18: Velocity vector field showing the temporal vortex propagation of the downburst outflows after impinging on the ground for the baseline case (008-1200-1800-2000) at $t/T_0 = 3.51, 3.86, 4.51, 4.68$. 
The strength of the near-ground vortex ring oriented clockwise (primary vortex) is quantified by the respective circulation value that is determined and plotted in Figure 3.19a, which shows that circulation increases as the vortex ring propagates until reaching a certain time $t$, and then starts decreasing as it dissipates. The temporal evolution of the circulations is scaled by the Lundgren et al. (1992) scaling variables and the scaled plot is presented in Figure 3.19b where a collapse of the curves onto a single curve is observed, showing the circulation peaks at $t/T_0 = 4.25$. This shows that the clockwise vortex ring near the ground (primary vortex) has similar evolution regardless of the peak cooling rate and that the Lundgren et al. (1992) scaling parameters maintain the location of the primary vortex ring in the radial outflow.

**Figure 3.19:** a) Time history of the magnitude of the primary vortex circulation for the simulation 008-1200-1800-2000. b) Non-dimensional temporal of primary vortex.
3.7.6 Limitations of the scaling approach.

Despite the successful application of the Lundgren et al. (1992) scaling parameters to downburst simulation using an ellipsoidal forcing cooling source as presented in previous sections of this chapter, there are some limitations to the approach employed to compute the scaling parameters \( R_0, T_0, V_0 \). The computation of \( \Delta \rho/\rho \) assumes the downburst downflow and outflow to be symmetric for simplicity, which is not the case in real downburst events (Hjelmfelt, 1988) and full-storm downburst simulations (Orf et al., 2012, 2014). Also, the scaling is well-achieved when average-value integrals are solved around the volume of the cooling source with a radius of 0.622 \( h_x \), which encompasses most of the downflow. It should be noted that the downbursts analyzed in this chapter are dry, so the scaling results presented are limited to dry downbursts.

3.8 Conclusions and recommendations

Full-scale downburst events were simulated using a cloud model with a forcing cooling source (CS). The results were normalized by the Lundgren et al. (1992) scaling parameters used in liquid release experiments. The non-dimensional density difference \( \Delta \rho/\rho \) was computed by spatially averaging the density inside and outside the forcing CS. The good collapse of the radial wind speed profile (temporal and radial) with RMS less than 10% shows that Lundgren et al. (1992) scaling variables can be implemented for full-scale downburst events simulated with the CS model. Furthermore, it allows comparison with the experimental liquid release models. It was previously demonstrated that the scaling method could be used to compare simulations when forcing the CS with the same cooling rate but for different geometrically scaled events (Oreskovic et al., 2018a). With the results of this chapter, it can be asserted that the scaling method can be used to compare simulations with a forcing CS regardless of the cooling rate or the size of the CS. The findings and conclusions are presented below:

- The Lundgren et al. (1992) parameters are not solely limited to liquid release models, but may also be used to scale downburst simulations that incorporate a forcing CS.
• The non-dimensional density $\Delta \rho/\rho$ is calculated by spatially averaging the density inside and outside the forcing CS, at each time step until the downdraft starts. The density inside the CS is integrated over a radius that is 62.2% of the CS radius ($h_x = h_y$), which is found to be the radius that encompasses the downdraft column. The density outside the CS is integrated over the volume inside the domain that is outside the CS. For simplicity in the use of cylindrical coordinates, a cylinder enclosed in the domain is used as the outside volume CS boundary. This approach resulted in calculating the scaling parameters $V_0$ and $T_0$ that resulted in scaling results with RMS less than 10%.

• The temporal profile of the non-dimensional density difference $\Delta \rho/\rho$ until the downdraft starts is the same regardless of the peak cooling rate of the CS. However, the peak $\Delta \rho/\rho$ is different. For the simulation baseline case, it is found to be 0.0192, which differs from the other cases analyzed.

• The non-dimensional density difference $\Delta \rho/\rho$ increases as the peak cooling rate increases, resulting in the same curve profile regardless of peak cooling rate, which collapses into a single curve when normalized, with a percentage difference less than 10% with respect to the baseline case ($q_{\text{max}} = 0.08$ K/s). This was achieved when the cooling rate was normalized by the peak cooling rate, and $\Delta \rho/\rho$ was normalized by $(\Delta \rho/\rho T_0/t)_{\text{max}}$ where $t_{\text{max}}$ is the time the peak cooling rate occurs, $t_{\text{max}} = 120$ s.

• The scaled temporal and vertical radial wind speed profiles preserved the shape and the radial wind speed location, with the non-dimensional radial wind speed occurring at $t/T_0 = 4.0$. The primary vortex ring radial location and propagation also were preserved for the different cases analyzed.

Based on the limitations identified, it is recommended the following for future work:

• The sensitivity analysis of $\Delta \rho/\rho$ should be performed for forcing CS with dimensions different from the baseline case. This research would be useful in analyzing the variation of the region of integration for forcing CS of different sizes, as well as how the value of $\beta$ varies.
• Investigate the application of the current scaling approach to wet downburst simulated numerically, to show how the inclusion of precipitation affects the scaling parameters.

3.9 References


Chapter 4

4 Simulation of downburst outflows with different ambient conditions using full-scale cooling source model.

4.1 Introduction

Downbursts are strong downdrafts that induce an outward “burst” of damaging winds on or near the ground (Fujita, 1978), with a velocity profile that differs from the neutral atmospheric boundary layer profile, as shown in Figure 4.1. A downburst with a damaging pattern less than 4 km is referred to as a microburst, whereas one with a damaging pattern greater than 4 km is referred to as a macroburst (Fujita, 1985). Microbursts are short-lived, lasting 5 to 10 minutes, and can be difficult to detect using non-Doppler radars or anemometers located on the ground (Fujita, 1985), whilst macrobursts can last from 5 to 30 minutes (Fujita, 1985). Downbursts can be classified into wet and dry downbursts based on the amount of precipitation observed on the ground (Fujita, 1985). Wet downbursts are those in which the raindrops do not evaporate completely before reaching the ground. On the contrary, in dry downbursts, the altitude of the base of the cloud generating the downdraft is sufficiently high to allow the evaporation of the raindrops before the downdraft reaches the ground (Fujita, 1985).

(a)  
(b)

Figure 4.1: Typical velocity profile for (a) neutral atmospheric boundary layer and (b) downburst outflow. Adapted from Lin (2010).
Precipitation and the environmental lapse rate (ELR) play an important role in the development of strong downbursts. Srivastava (1985) discovered that the magnitude of the downdraft's vertical air velocity increases as the ELR, the rainwater mixing ratio at the top of the downdraft, and the relative humidity of the environment increase. It does, however, decrease as the mixing of environmental air into the downdraft increases (Srivastava, 1985, 1987). Similarly, Proctor (1988) found out that microbursts were primarily driven by cooling due to the evaporation of rain and the melting of the hail. Stronger downbursts were observed when the ELR approximated the dry adiabatic lapse rate (Proctor, 1988). This finding was confirmed by Hjelmfelt (1988), which included the loading and melting of graupel, along with the loading and evaporation of rain to reproduce a downburst event. The approach by Proctor (1988) and Hjelmfelt (1988) was more sophisticated because the model used by Srivastava (1985) included only precipitation in the form of rain and was a one-dimensional model.

Proctor's (1988, 1989) sensitivity study about the effect of falling precipitation on the physics, dynamics, and time-dependent structure of simulated downbursts revealed that stable ELR ($\Gamma < 6.5$ K/km) results in a weak downburst. However, it should be noted that ELR alone cannot define the environmental conditions in which a downburst or a downburst-producing storm forms and develops. Downbursts may not occur when the environment is conditionally unstable (6.5 K/km < $\Gamma$ < 9.8 K/km), although it is a favorable environment for the formation of thunderstorms. Srivastava (1985) showed that high ELR and high rainwater mixing ratio are necessary for intense downdrafts. This shows that precipitation and ELR should both be considered as environmental conditions. However, due to the computational cost involved with the inclusion of precipitation, studies have been carried out using subcloud models, with a focus on the ELR only (Orf, 1997; Mason et al., 2009).

Orf (1997) investigated the effects of the ELR on the strength of a traveling downburst using a subcloud model. The downburst was initiated using the same approach as Anderson et al. (1992), by imposing an ellipsoidal forcing cooling source (CS) with horizontal and vertical half-widths of 1200 m and 1800 m, respectively, and a peak cooling rate of magnitude 0.03 K/s. The elevation of the centre of the forcing CS, 2000 m ABL, was
consistent with microburst simulations conducted by Knupp (1989) and Hjelmfelt et al (1989), which found that downdraft initiation occurred below the melting level, around 2 km ABL (Orf, 1997). The simulations were carried out at lapse rates of 8.26 K/km, 7.76 K/km, and 6.76 K/km, and then compared with the dry adiabatic lapse rate, 9.80 K/km. As the lapse rate decreased, the magnitude of the surface horizontal winds and the spatial extend decreased, due to the weak downdraft produced (Orf, 1997). In addition, roll vortex circulations weakened as the lapse rate decreased, and were absent at $\Gamma = 6.76$ K/km (Orf, 1997). These findings were found to be consistent with Proctor's (1989) axisymmetric simulations in conditionally unstable environmental conditions.

Another study on the effects of the ELR on the horizontal outflows was conducted by Mason et al. (2009), using a subcloud model with the same forcing CS (Anderson et al., 1992) to initiate the downdraft. Simulations were carried out at the dry adiabatic lapse rate (9.8 K/km) and 7.5 K/km, with the peak cooling rate of magnitude 0.08 K/s. Turbulence was modeled with the scale-adaptive simulation (SAS) closure scheme of Menter and Egerov (2005). Their results showed that the intensity of the outflows after impingement decreased by 19% as the lapse rate decreased to 7.5 K/km (Mason et al., 2009). This decrease was due to the smaller temperature difference between the forcing function and the ground plane, resulting in a smaller density difference inside the downdraft. This reduced the buoyancy force, leading to the reduction of the downdraft velocity (Mason et al., 2009). Like Proctor (1988), Mason et al. (2009) also found out that the lapse rate only affected the magnitude of the peak wind speed, not the structure of the outflow. However, the study was carried out with one peak cooling rate only,

Despite the quantitative analysis by Orf (1997) and Mason et al. (2009) on the effect of ELR on the horizontal peak wind velocity after the downdraft impinges on the ground, there are still gaps to be filled, such as quantitative analysis on the effects of the ELR on the downdraft structure, and how the decrease of the downdraft intensity and the ELR affect the downdraft evolution. This chapter fills those gaps and adds more to the current body of knowledge by:
• Investigating the effects of the environmental lapse rate on downdraft development before it impinges the ground (Section 4.4.1), and in the peak radial wind speed (Section 4.4.2).
• Investigation the application of the Lundgren scaling parameters introduced in the previous chapter, for CS simulations at different lapse rates (Section 4.4.3).
• Carrying out a detailed quantitative study of the effects of the environmental lapse rate on the downburst structure, and how the downburst intensity (quantified by the peak cooling rate of the CS) contributes to the structure of downburst when lapse rate is lower than the dry adiabatic lapse rate (9.80 K/km) (Section 4.4.4).
• Studying the effects of ELR on the vertical profile of the radial wind speed (Section 4.4.5).

The subcloud model used in this study is dry and does not include any microphysics, which is reasonable since this research focuses on the dynamics of the downdraft and the radial outflow, and not on microphysics nor downburst formation.

4.2 Environmental lapse rate (ELR) – Mathematical formulation

The effects of the lapse rate on downbursts are investigated in this chapter. This section introduces the mathematical formulation of the temperature lapse rate and theories that are useful in this chapter. Consider a dry sinking air parcel (dry downdraft) as shown in Figure 4.2. Since the downdraft temperature is lower than the ambient temperature, it gains heat per unit of mass $dq_e$. As a result, the internal energy per unit of mass $du_i$ of the parcel changes due to the increase of the parcel temperature, $du_i = c_v \, dT$. As the downdraft develops, it compresses due to the higher pressure (p) encountered as it sinks, resulting in work $dw$ per unit of mass being done on it, $dw = pdv$ (Jacobson, 2005). Applying the first law of thermodynamics,

$$dq_e + pdv = c_v dT$$

(4.1)
where $c_v$ is the specific heat of dry air at constant volume, $T$ is the temperature, and $v$ is the downdraft volume per unit of mass, $v = V/m = 1/p$. From equation of state, $pv = RT$. Then

\[
pdv = RdT - vdp \tag{4.2}
\]

Combining (4.1) with (4.2) and dividing by $dz$, yields

\[
\frac{dq_e}{dz} = c_p \frac{dT}{dz} - v \frac{dp}{dz} \tag{4.3}
\]

\[\text{Figure 4.2: Representation of a sinking air parcel in a quiescent environment.}\]

Remembering that temperature lapse rate ($\Gamma$) is the negative change in temperature with height, and that $p$ obeys the hydrostatic equation (Jacobson, 2005), then (4.3) is simplified to

\[
\frac{dq_e}{dz} = -c_p \Gamma + g \tag{4.4}
\]
where \( g = 9.8 \text{m/s}^2 \) is the constant of gravity. This equation shows that environmental lapse is related to the heat exchange between the downdraft parcel and the environment. For the adiabatic case, \( dq_e = 0 \), yields the dry adiabatic lapse rate \( \Gamma_d \).

\[
\Gamma = \Gamma_d = \frac{g}{c_p} = 9.8 \text{ K/km} \tag{4.5}
\]

If there is heat exchange such as \( q_e > 0, dq_e/dz > 0 \), then

\[
\Gamma < \frac{g}{c_p} \Rightarrow \Gamma < 9.80 \text{ K/km} \tag{4.6}
\]

This shows that the downdraft gains heat when the environmental lapse rate is less than the dry adiabatic lapse rate. This concept will aid in the interpretation of the effects of the environmental lapse rate on the downburst downdraft and on the outflow. It should be noted that the potential temperature of the environment does not change when \( \Gamma = \Gamma_d = 9.80 \text{ K/km}, d\theta/dz = 0 \) (Jacobson, 2005). More information on the lapse rate can be found in textbooks on atmospheric science (Jacobson, 2005; Vallis, 2017).

### 4.3 Methodology

This research employs the same methodology as the previous chapter, including the same computational domain, mesh, and boundary conditions. A \( 9.6 \text{ km} \times 9.6 \text{ km} \times 4 \text{ km} \) computational domain with horizontal mesh grid spacing of \( \Delta x = \Delta y = 10 \text{ m} \) is used. Furthermore, a vertical stretching mesh based on Wilhelmson and Chen (1982) is used, with the first grid point above the ground at \( \Delta z = 1 \text{ m} \) and stretching to \( \Delta z = 50 \text{ m} \) at the top of the domain using 160 horizontal planes. The lateral sides of the domain are treated as open-radiative surfaces to allow the flow to enter and exit the domain. Like previous works (Mason et al., 2009; Vermeire et al., 2011a; Oreskovic et al., 2018a,b), the bottom surface is treated as a semi-slip surface with roughness length of \( z_0 = 0.10 \text{ m} \). The heat fluxes between the bottom surface and the air are not included. The top surface of the domain is set to be a free-slip surface. The atmosphere is considered quiescent with a constant and uniform ground surface temperature of \( 300 \text{ K} \), and the simulations were carried out at different ELR. A time step \( \Delta t = 0.05 \text{ s} \) with 10 acoustics sub-steps was used
to maintain computational stability while achieving time-step independence (Oreskovic, 2016), and all simulations were run for 10 minutes, enough time to allow for the decay of
the vortices in the simulated downburst outflows.

4.4 Numerical simulation data

This chapter investigates the effects of changing the environmental lapse rate for
downburst simulations carried out in Shared Hierarchical Academic Research Computing
Network (SHARCNET) using CM1 (Bryan, 2002) with a forcing CS model. The forcing
CS has an ellipsoidal shape of same dimensions and peak cooling rate magnitude ($q_{\text{max}}$) as
the baseline case in previous CS simulations (Vermeire et al., 2011a; Oreskovic et al.,
2018a), $h_x = h_y = 1200$ m, $h_z = 1800$ m, $h_c = 2000$ m, and $q_{\text{max}} = 0.08$ K/s, where $h_x$, $h_y$, $h_z$
are the half-widths of the CS and $h_c$ is the distance from the ground to the centre of the CS.
To analyze the ELR effects in downbursts of different intensities, the same simulations are
also conducted with $q_{\text{max}}$ of 0.10 K/s, 0.06 K/s, and 0.04 K/s. These values lead to high
horizontal wind outflows (Oreskovic et al., 2018a), allowing a better analysis of the effects
of the ELR. The simulations are carried out at four different lapse rates: 9.80 K/km, 8.26
K/km, 7.76 K/km, and 6.76 K/km. These are the same values used by Orf (1997) and are
in the range of a conditionally unstable environment ($6.5$ K/km $< \Gamma < 9.8$ K/km). The
temperature and the potential temperature profile due to the corresponding ELRs are shown
in Figure 4.3. The simulations are named in the format LapseRate-PeakCoolingRate-h_x-
h_z-h_c, and the radial wind speed at a given ELR value is denoted by $u_r$. Table 4.1 lists the
simulations analyzed in this chapter, and Figure 4.4 shows the CS shape and parameters.

![Diagram](image-url)
Figure 4.3: Temperature (a) and potential temperature (b) profiles due to the environmental lapse rate.

Table 4.1: Downburst simulations carried with different environmental lapse rates.

<table>
<thead>
<tr>
<th>Simulations in CM1</th>
<th>$q_{\text{max}}$ (K/s)</th>
<th>$\Gamma$ (K/km)</th>
<th>$h_x$, $h_y$ (m)</th>
<th>$h_z$ (m)</th>
<th>$h_c$ (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>980-008-1200-1800-2000</td>
<td>0.08</td>
<td>9.80</td>
<td>1200</td>
<td>1800</td>
<td>2000</td>
</tr>
<tr>
<td>826-008-1200-1800-2000</td>
<td>0.08</td>
<td>8.26</td>
<td>1200</td>
<td>1800</td>
<td>2000</td>
</tr>
<tr>
<td>776-008-1200-1800-2000</td>
<td>0.08</td>
<td>7.76</td>
<td>1200</td>
<td>1800</td>
<td>2000</td>
</tr>
<tr>
<td>676-008-1200-1800-2000</td>
<td>0.08</td>
<td>6.76</td>
<td>1200</td>
<td>1800</td>
<td>2000</td>
</tr>
</tbody>
</table>

| 980-004-1200-1800-2000 | 0.04                   | 9.80            | 1200            | 1800      | 2000      |
| 826-004-1200-1800-2000 | 0.04                   | 8.26            | 1200            | 1800      | 2000      |
| 776-004-1200-1800-2000 | 0.04                   | 7.76            | 1200            | 1800      | 2000      |
| 676-004-1200-1800-2000 | 0.04                   | 6.76            | 1200            | 1800      | 2000      |

Figure 4.4: A 2D representation of the ellipsoidal cooling source used to initiate the downdraft.
4.5 Results and discussion

This section presents and analyzes the results of simulations performed with CM1 and a forcing CS. The effects of the ELR on the structure of the outflow, the radial wind speed profile and corresponding peak values are examined.

4.5.1 The effects of environmental lapse rate on the downdraft evolution.

The effects of the ELR on the downdraft evolution are investigated by looking into the effects on the radial profile of the vertical velocity (w) at some instants (60 s, 120 s, 180 s, and 240 s) before the downdraft impinges the ground. These time instants are selected arbitrarily with special attention to 120 s, when the cooling source reaches the peak cooling rate. The altitude analyzed at each instant is the one in which the peak vertical velocity (w) occurs at the corresponding instant for the baseline case (980-008-1200-1800-2000), which is found to be 1905, 1872, 1641, and 848 m AGL, respectively. Figure 4.5 shows the effects of the ELR on the radial profile of the vertical velocity of the downdraft as it develops, for the baseline case. At t = 60 s, the vertical velocity is approximately zero regardless of the lapse rate value (Figure 4.5a), with the dry adiabatic case (9.80 K/km) reaching a peak vertical velocity (w_{max}) of -0.33 m/s, and the lowest lapse rate case (6.76 K/km) reaching -0.32 m/s. The difference is negligible at this instant. The same can be observed at t = 120 s (Figure 4.5b), when the cooling source reaches the peak cooling rate (q_{max} = 0.08 K/s), where there is no significant difference in the w_{max} for different lapse rates, w_{max,9.80} = -4.24 m/s, w_{max,6.76} = -3.96 m/s. However, as time elapses, the difference becomes evident as seen in Figure 4.5c and Figure 4.5d, where a lower lapse rate led to a lower peak vertical velocity. At t = 240 s, it is observed w_{max,9.80} = 29.7 m/s and w_{max,6.76} = 22.6 m/s, whereas other lapse rate peak velocities are in-between these cases. This difference is expected since in the dry adiabatic case (9.80 K/km), the downdraft develops adiabatically and the environmental potential temperature is constant (Figure 4.3b), preserving so its driving force (buoyancy). In the other cases, however, the heat exchange between the environment and the downdraft, with the colder downdraft gaining heat, results in the decrease of the buoyancy acceleration (force), and since the downburst is dry, the velocity of the downdraft decreases. This decrease reflects on the evolution of the
downburst, causing a delay in the downdraft and the outflow propagation when ELR is less than 9.80 K/km, which is discussed in detail in the following section. The same behaviour is observed in the other $q_{\text{max}}$ cases (not shown here), which is expected as the $q_{\text{max}}$ does not affect the structure of the downdraft, but increases only the peak velocity (Oreskovic et al., 2018b).

![Graphs](attachment:graphs.png)
4.5.2 The effects of ELR on the peak radial wind speed.

**Figure 4.6** shows the effects of the ELR on the temporal profile of the outflow peak radial wind speed ($u_{r,max}$). The strength of the downburst radial outflow, quantified by $u_{r,max}$, decreases as the ELR decreases, as shown in the time history of the peak radial wind speed in **Figure 4.6**. A peak radial wind speed of 52.0 m/s when $\Gamma = 9.80$ K/m ($u_{r,9.8} = 52$ m/s) is observed for a peak cooling rate ($q_{\text{max}}$) of 0.08 K/s (**Figure 4.6a**), which is significantly reduced (23.8%) to 39.6 m/s when $\Gamma = 7.76$ K/m ($u_{r,7.76} = 39.6$ m/s) with the same $q_{\text{max}}$, leading to the ratio $u_{r,7.76}/u_{r,9.8} = 0.76$. A similar decrease was observed by Mason et al. (2009), which found a ratio of the peak velocities $u_{\text{max},7.5}/u_{\text{max},10} = 0.8$ when investigating the effects of the ELR on downburst outflow. The delay observed in the downdraft evolution is also reflected in the radial outflow propagation as seen in the time history of the peak radial wind speed in **Figure 4.6a**, which shows that $u_{r,max}$ occurs around $t = 330$ s when $\Gamma = 9.80$ K/m, whereas it occurs seconds later when $\Gamma < 9.80$ K/km.

A similar ELR effect on the peak radial wind speed is observed when the peak cooling rate of the forcing CS is reduced to 0.04 K/s (**Figure 4.6b**). However, when the ELR and the downdraft intensity ($q_{\text{max}}$) are decreased to 6.76 K/km and 0.04 K/s respectively, the temporal peak radial speed profile shape changed significantly (**Figure 4.6b**), with the peak...
wind speed decreased to 21 m/s. This change is also reflected in the contour of the potential temperature at the time the peak wind speed occurs in that specific case (667-004-1200-1800-2000) as seen in Figure 4.7, which shows that the downburst outflow is warmer than the environment. Since warmer air tends to move upwards, this implies that some outflow would rise, resulting in the decrease of the peak radial wind speed. This decrease in the peak radial wind speed is also due to the environment's stability condition. As the ELR approaches 6.50 K/km, the environment is near the stable condition, which is unfavorable for downburst formation or strong downdrafts.

![Graph showing time history of peak radial wind speed with different lapse rates](image)

**Figure 4.6:** Time history of the peak radial wind speed \(u_{r,\text{max}}\) with different lapse rates \((\Gamma)\): 9.80 K/km, 8.26 K/km, 7.76 K/km, 6.76 K/km. a) \(q_{\text{max}} = 0.08\) K/s. b) \(q_{\text{max}} = 0.04\) K/s.
4.5.3 Application of the Lundgren et al. (1992) scaling parameters

This section investigates the application of the Lundgren et al. (1992) scaling parameters, R₀, T₀, V₀, introduced in the previous chapter, to scale CS simulations when the ELR is varied. The non-dimensional density difference (Δρ/ρ) for each case is evaluated using the approach discussed in the previous chapter. The computed Δρ/ρ and the scaling parameters R₀, T₀, V₀ are listed in Table 4.2, where it is observed that buoyancy, quantified by Δρ/ρ, decreases with the decrease of the ELR regardless of the intensity of the downdraft (q_{max}), as discussed before. Figure 4.8 shows the normalized plot of temporal peak radial wind speed for the baseline case (008-1200-1800-2000) at different lapse rates. The shape of the curves is preserved by the Lundgren et al. (1992) scaling parameters, as well as the time in which the peak non-dimensional peak radial speed occurs, t/T₀ ≈ 4.0. However, less profile similarity is observed when the ELR is less than 9.80 K/km, as visualized in Figure 4.8.
This can also be seen in Figure 4.9, which presents the scaled temporal peak radial wind speed profiles of all simulations. When the ELR is equal to the dry adiabatic lapse rate (9.80 K/km), the profile shapes are similar regardless of the peak cooling rate of the CS (q_{max}), as shown and discussed in the previous chapter. When the ELR is less than 9.80 K/km, however, less profile similarity is observed since the collapse of the curves into a single line is poor. This implies that the curve shapes are not similar when ELR is less than 9.80 K/km, which could be due to external factors like the downdraft heat gain, which is not observed in the dry adiabatic cases (9.80 K/km). It should be noted that as the ELR approaches 9.80 K/km (with a high peak cooling rate), a better similarity is observed.

**Table 4.2: The calculated Δρ/ρ and the Lundgren et al. (1992) scaling parameters for each simulation.**

<table>
<thead>
<tr>
<th>Simulations</th>
<th>Δρ/ρ</th>
<th>R₀</th>
<th>T₀</th>
<th>V₀</th>
</tr>
</thead>
<tbody>
<tr>
<td>980-008-1200-1800-2000</td>
<td>0.0192</td>
<td>1373</td>
<td>85.38</td>
<td>16.08</td>
</tr>
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<td>93.88</td>
<td>14.62</td>
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</tr>
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<td>126.84</td>
<td>10.83</td>
</tr>
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</table>

Figure 4.8: Normalized plot of the temporal peak radial wind speed for the baseline case with different ELR.
4.5.4 The effects of environmental lapse rate on outflow structure and radial evolution.

Environmental lapse rate has a significant effect on the development of severe downburst events. Figure 4.10 shows the effects of lapse rate on the radial outflow structure for $q_{\text{max}} = 0.08 \text{ K/s}$ when the leading edge is at $r = 2.10 \text{ km}$ for three different lapse rate cases: 9.80 K/km (Figure 4.10a), 7.76 K/km (Figure 4.10b), and 6.67 K/km Figure 4.10c. This radial location is chosen since the outflow has developed enough so that vortex rings can be visualized, allowing a detailed study of the structure of the downburst. The structure of the downflow and the radial outflow remains the same despite the decrease in the lapse rate as seen in the vector field in Figure 4.10. This is found to agree with Mason et al. (2009) who inferred that the lapse rate did not affect the structure of the outflow. However, when the peak cooling rate is decreased to 0.04 K/s, the structure changes significantly when the lapse rate is 6.76 K/km, as shown in Figure 4.11. This shows that the structure of the downburst remains the same if the intensity ($q_{\text{max}}$) of the downdraft is higher enough so that it reaches the ground before losing the negative buoyancy due to heat gained when the lapse rate is less than 9.80 K/km, resulting in outflow warmer ($\theta = 302 \text{ K}$) than the environment, as seen in Figure 4.11. The study by Mason et al. (2009) was limited to one
peak cooling rate ($q_{\text{max}} = 0.08 \text{ K/s}$), in which the structure remains constant. As shown here, the lapse rate does affect the structure of the outflow when the peak cooling rate is lower.

a)

![Diagram](980-008-1200-1800-2000.png)

$t = 335 \text{ s}$

b)

![Diagram](776-008-1200-1800-2000.png)

$t = 360 \text{ s}$
c) Figure 4.10: Contours of potential temperature and velocity vector showing the structure of the downburst radial outflows at different ELR, at \( r \approx 2.1 \text{ km} \) for \( q_{\text{max}} = 0.08 \text{ K/s} \). a) \( \Gamma = 9.80 \text{ K/km} \). b) \( \Gamma = 7.76 \text{ K/km} \). c) \( \Gamma = 6.76 \text{ K/km} \)

Figure 4.11: Contour of potential temperature and velocity vector showing the structure of the downburst radial outflows for \( q_{\text{max}} = 0.04 \text{ K/s} \) and \( \Gamma = 9.80 \text{ K/km} \), at the same radial location.
Focusing on the time at which the simulations cross the radial location \( r = 2.10 \) km (Figure 4.10 and Figure 4.11), it can be seen that the downdraft evolution delay observed earlier (Figure 4.5) is also reflected in the evolution of the outflow. There is a delay in the radial outflow evolution when the environmental lapse rate is less than \( 9.80 \) K/km. The instant at which the leading edges are at the same radial location is different, with the leading-edge crossing \( r = 2.10 \) km at \( t = 340 \) s when \( \Gamma = 9.80 \) K/km, and at \( t = 360 \) s when \( \Gamma = 7.76 \) K/km (Figure 4.10a and b). The radial location of \( 2.10 \) km is passed 20 s later when the lapse rate is \( 7.76 \) K/km, and much later when \( \Gamma = 6.67 \) K/km (Figure 4.10c). The delay in the radial outflow propagation can be seen in Figure 4.12, which shows the radial wind speed profile for \( q_{\text{max}} = 0.08 \) K/s simulation at different ELRs, at the time (\( t = 330 \) s) and the altitude (\( z = 113.3 \) m) the peak radial wind speed occurs for the dry adiabatic case (\( 9.80 \) K/km). This shows that at the same time and altitude, the outflow with lower ELR is at a radial distance less than that observed at a higher ELR.

![Figure 4.12: Radial evolution of the outflow for different ELR at the same time and altitude: 330 s and 113.3 m.](image)
Figure 4.13 aids in the visualization of the outflow delay, by showing the radial outflow evolution of the downburst at the lapse rate values of 9.80 K/km, 7.76 K/km, 6.76 K/km, at the same instant, \( t = 450 \) s. This time is selected since it would show that the delay remains until the outflow dissipates. At \( t = 450 \) s, the leading edge of the outflow is at 3.0 km when \( \Gamma = 9.80 \) K/m (Figure 4.13a), whereas it is at 2.7 km when \( \Gamma = 7.76 \) K/m (Figure 4.13b), equivalent to the decrease of 9.5%. The leading edge when \( \Gamma = 6.76 \) K/m is at 2.5 km at the same instant. As discussed before, this delay is due to the reduction of the downdraft’s driving force (buoyancy) caused by the heat exchange between the downdraft and the environment when the ELR is less than the adiabatic lapse rate (9.80 K/km), as seen in the computed \( \Delta \rho/\rho \) in Table 4.2. Since precipitation that enhances the driving force is not included in the subcloud model used, the downdraft loses strength before reaching the surface when ELR \( < 9.80 \) K/km.

\[ a) \]
Figure 4.13: Contours of potential temperature showing the radial evolution of the downburst outflow for $q_{\text{max}} = 0.08$ K/s, at different environmental lapse rates. (a) $\Gamma = 9.80$ K/km. (b) $\Gamma = 7.76$ K/km. (c) $\Gamma = 6.76$ K/km.
4.5.5 The effects of ELR on the vertical radial wind speed.

To study the effects of ELR on the vertical radial wind speed profile, two radial locations were selected at the time the peak radial wind speed occurs at each simulation: \( r = 1.20 \) km (for all simulations) and the radial location at which peak radial wind speed occurs at each simulation. The radial location \( r = 1.20 \) km is less than the radial location in which the peak radial speed at each simulation occurs. It is chosen because less vortex rings are seen at this radial location when compared with the peak radial speed location as shown by Vermeire et al. (2011a), resulting in a typical (Lin, 2010) downburst vertical speed profile. Figure 4.14 shows the effects of the ELR on the vertical profile of the radial wind speed from 0 km to 800 km AGL at \( r = 1.20 \) km, at the time that the peak radial wind speed at each simulation occurs.

At this radial location, each simulation showed a typical velocity profile shape obtained in downburst modeling, either numerically (Proctor, 1988; Vermeire et al., 2011a; Orf et al., 2012; Li et al., 2012; Aboshosha et al., 2015; Oreskovic et al., 2018a) or experimentally (Graat, 2020; Jariwala, 2021) (Figure 4.14). The decrease of the near-ground outflow peak radial speed is observed with the decrease of the ELR in Figure 4.14, where strong winds occur when ELR is 9.80 K/km before decreasing to nearly zero at the surface due to the boundary conditions. The vertical radial wind speed profile shape is similar regardless of the environmental lapse rate for \( q_{\text{max}} = 0.08 \) K/s, with exception of 6.76 K/km. This difference is due to the higher decrease in the radial wind speed when the ELR approaches the absolutely stable environment condition (0 K/km < \( \Gamma < 6.50 \) K/km). The peak radial wind speed vertical location is affected by the decrease of the ELR, with it decreasing from 18.4 m to 12.0 m when ELR decreased from 9.80 K/km to 6.76 K/km (Figure 4.14). The decrease of the corresponding peak height location at \( r = 1.20 \) km is due to the gain of heat during the downdraft development when ELR < 9.80 K/km, resulting in a very weak outflow at that location by the time outflow leading-edge reaches the location of the peak radial wind speed.
However, at the radial location and time at which each simulation’s peak radial wind speed occurs, a different vertical radial wind speed profile shape is observed, as shown in Figure 4.15. The peak radial wind speed occurs at the radial locations 1.93, 1.59, 1.52, and 1.50 km, when the environmental lapse rate is 9.80 K/km, 8.26 K/km, 7.76 K/km, and 6.76 K/km, respectively. At these radial locations, Figure 4.15 shows a negative radial wind speed (radial speed in the opposite r-direction) near the ground with a peak of -27 m/s for $\Gamma = 9.80 \text{ K/km}$ and around -20 m/s for lapse rate less than 9.80 K/km. This radial speed is caused by a clockwise vortex ring that is observed near the ground at the time and radial location the peak wind speed occurs. The vortex ring is shown in Figure 4.16 for the baseline case ($\Gamma = 9.80 \text{ K/km}$), which is caused by the roughness of the ground surface. Hjelmfelt (1988) previously observed the same vortex ring at the peak velocity location, ranging from 50 m to 150 m AGL. The peak radial wind speed found in the present research
when the peak cooling rate of the CS is 0.08 K/s fall in that range: 150 m ($\Gamma = 9.80$ K/km), 89.5 m ($\Gamma = 8.26$ K/km), 89.5 m ($\Gamma = 8.26$ K/km), and 97.1 m ($\Gamma = 6.76$ K/km). It should be noted that the vertical locations of the peak wind speed seem to be random since at 6.76 K/km is higher than at 9.80 K/km. This could be due to the vortices observed at those locations. The vertical radial wind speed profiles investigated showed that the typical downburst outflow profile is observed at a radial location less than that of the peak wind speed radial location in CS simulations.

Figure 4.15: Vertical profile of the radial wind speed for different lapse rates at $q_{\text{max}} = 0.08$ K/s, at the radial location and time the peak wind speed at each simulation occurs.
Limitations of the current study.

Despite the intriguing findings of the environmental effects on downburst downdraft and outflow evolution, there are some limitations that should be discussed. The environmental effects found are only limited to the effect of the environmental lapse rate. However, downbursts are affected by environmental conditions such as the environmental lapse rate, precipitation, and the mixing of environmental air (Srivastava, 1985), which are not considered in this study since the subcloud model used is completely dry. Environmental lapse rate alone is insufficient for studying the effects of environmental conditions on downbursts. Therefore, it is recommended that future studies use a subcloud model that includes precipitation as well for more general results. This would also help to advance research on downbursts using subcloud models that include precipitation, which has only been done by a few researchers (Srivastava, 1985, 1987; Proctor, 1988) so far.

4.6 Conclusions

Full-scale downburst events at various environmental lapse rates were simulated using a cloud model with a forcing cooling source by Anderson et al. (1992). The ambient lapse rate values used in the analysis were the same as those used by Orf et al. (1997). The obtained results reinforced that the strength of the downbursts is affected by the ambient
lapse rates, as previously found by Proctor (1988) and Mason et al. (2009), with high peak wind speed observed when the environmental lapse rate equals the dry adiabatic lapse rate. The key findings from the current study are summarized below.

- ELR less than the dry adiabatic lapse rates (9.80 K/km) results in delayed downdraft development, which is reflected in the downburst radial outflow evolution. This delay leads to the outflow reaching the peak radial wind speed and dissipation much later when the ELR < 9.80 K/km.

- The structure of the downflow and the outflows of the downburst does not change regardless of the ambient lapse rate value if the intensity of the downburst is high enough so that the downdraft reaches the ground still negatively buoyant. The peak cooling rate of 0.08 K/s maintains the downdraft structure constant. However, when decreased to 0.04 K/s, the structure of the downburst changed, with the outflow being warmer than the environment. This finding shows that the downburst structure does not stay the same regardless of the ELR, as concluded in previous work (Mason et al., 2009).

- The vertical peak radial wind speed occurs at 150 m AGL, which is higher than the vertical location when ELR is less than 9.80 K/km. The vertical peak locations are in the range of those downbursts by Hjelmfelt (1988), which was based on a real event in Colorado.

The next chapter uses the subcloud model CM1 to investigate a CS template able of producing a downburst similar to those produced in the more realistic cloud model simulations.

4.7 References


Chapter 5

5 Investigation of a cooling source template that produces downburst outflows similar to those produced by full-storm cloud models.

This chapter investigates cooling source (CS) templates able to produce the same downburst outflows as those produced by the full-cloud model simulations. Subcloud model with a CS will be used for this investigation.

5.1 Introduction

A downburst is a strong downdraft that impinges on the ground and spreads out radially, with horizontal wind speed able to reach 75 m/s (Fujita, 1978). Downbursts happen during thunderstorms in which the cumulonimbus clouds are formed. Realistic downburst storm simulations have been carried out using full-cloud models (Hjelmfelt et al., 1989; Anderson & Straka, 1993; Orf et al., 2012, 2014). These simulations include the formation of the thunderstorm cloud producing the downbursts and precipitation, whereas subcloud models focus more on the dynamics of the downburst outflows and the downdraft below the cloud base (Hjelmfelt et al., 1989). Hjelmfelt et al. (1989) used a two-dimensional numerical full-cloud model that included the melting of ice particles. The cloud model was constituted by nonlinear partial differential equations: the three equations of motion, the thermodynamic equation, and the water conservation equation (for liquid, solid (ice), and vapour). A domain of 19.2 km × 19.2 km and a uniform grid spacing of 200 m were used. The simulations were performed using the atmospheric sounding taken in Denver in July 1982, which were favorable for the formation of downbursts (Caracena et al., 1983; Wakimoto, 1985). As a result, a cloud with a structure and height similar to those observed in field measurement campaigns was simulated, with the cloud base occurring around 2.2 km AGL and the top cloud reaching 9.6 km (Hjelmfelt et al., 1989). The storm generated a downburst with the outflow reaching a speed of 22 m/s, which is comparable with the 25 m/s obtained from averaging the peak wind speed of 6 microbursts observed in JAWS (Hjelmfelt, 1988; Roberts & Wilson, 1989).
A much stronger downburst was produced by Straka and Anderson (1993), and by Orf et al. (2012, 2014). Using an atmospheric sounding taken from actual downburst events near Redstone Arsenal in Alabama, Straka and Anderson (1993) simulated a storm capable of producing short periods of heavy rain and large hail. The simulation was carried out in a three-dimensional cloud model using an isotropic grid resolution of 500 m in a full domain of size 25 km × 25 km in the horizontal and 19 km in the vertical (Straka & Anderson, 1993). Turbulence was modeled using the closure scheme of Klemp and Wilhelmson (1978), which differed from the nonlinear eddy mixing used by Hjelmfelt et al. (1989). The resulting storm led to the formation of clouds and precipitation, which induced the formation and development of the downdraft, generating the surface outflows after impinging on the ground (Anderson & Straka, 1993). The storm was able to generate a downburst with a peak downdraft velocity ranging from 4 to 12 m/s, and the peak wind outflow reaching 25 m/s at 125 m ABL (Straka & Anderson, 1993). A downburst with a higher peak wind speed, 37 m/s, was obtained by Orf et al. (2012, 2014).

Orf et al. (2012) employed the Bryan cloud model 1 (CM1) (Bryan & Fritsch, 2002) to carry out a downburst-producing thunderstorm simulation in a computational domain of 92 km x 92 km x 14 km with a fine horizontal grid spacing of Δx = Δy = 20 m and a stretching mesh vertically, where Δz = 5 m immediately above the ground, stretching to 95 m at the top of the domain. The momentum equations were solved using a third-order Runge-Kutta time differencing scheme and fifth- or sixth-order vertical (horizontal) advection, while turbulence diffusivities were solved using a subgrid turbulence model based on Deardorff (1990). The model was initialized by the atmospheric base state — temperature, humidity, pressure, and horizontal winds — from a sounding identified by Brown et al. (1982) and Wakimoto (1985), which represents conditions leading to the formation of dry downbursts over the High Plains of the USA (Orf et al., 2012). In addition, a warm bubble temperature perturbation was used to impose an ellipsoid of positive buoyancy in the lower atmosphere (Orf et al., 2012). This resulted in a simulation of the cumulonimbus cloud with the cloud base observed to be around 3300 m AGL, generating a downdraft column of diameter estimated to be 1300 m, with a density perturbation (Δρ/ρ) of 1.33% different from the ambient, about 4 K in 300 K (Oreskovic et al., 2018b). This
led to a downburst event with two locations (A and B) of strong instantaneous near-surface horizontal wind ($V_{Hmax}$) occurring on opposite sides oriented on the same axis, with A being on the eastern flank of the downdraft, and B on the western flank (Figure 5.1) (Orf et al., 2012). Location A reached the peak instantaneous horizontal wind of 35.9 m/s at an elevation of 38 m AGL at 606 s, whereas location B reached 37.3 m/s at an elevation of 19 m AGL at 628 s (Orf et al., 2012). The 606 s and 628 s were measured from the instant the downdraft begins, which is at 3000 s after the start of the simulation. The locations A and B of the downburst had different spatial and temporal outflow evolutions as shown by Orf et al. (2012).

Figure 5.1: The two locations of the maximum instantaneous horizontal wind speed produced by the downburst-producing thunderstorm simulation by Orf et al. (2012). Adapted from Orf et al. (2012).

The data were post-processed using the circumferential averaging approach developed by Orf et al. (2012, 2014), in which the asymmetric outflow is transformed into an axisymmetric outflow. The approach carries out a circumferential statistical analysis at an
imposed constant-radius periphery representing an axisymmetric “template” over the data set, to relate the peak wind speeds to the spatially-averaged value around the periphery (Orf et al., 2012), resulting in a single vertical plane \((r, z)\) of data produced at each time step, where \(r\) and \(z\) denote the altitude and radial location respectively. This resulted in circumferentially-averaged velocity profiles that are suitable for comparing with results obtained from simpler engineering models like the cooling source (CS) model (Orf et al., 2012). Both locations reached a peak circumferentially-averaged speed of 17 m/s at a radial location of 1.5 km (Orf et al., 2014).

Full-cloud model simulations have shown that precipitation phase change is responsible for the negative buoyancy (Hjelmfelt et al., 1989), and have demonstrated that cloud models can produce realistic simulations of downbursts (Orf et al., 2012). However, due to the computational cost associated with full-cloud simulations, much simpler subcloud models have been used to simulate downburst events. Proctor (1988) simulated a downburst by including precipitation in the cloud model and focused on the downdraft below the cloud base since the entire cloud life cycle and structure of the downburst-producing thunderstorms were not simulated. The isolated downdraft was initiated by setting a distribution of precipitation as the top boundary condition, which led to an increase in the mass and density of air as the precipitation fell in the domain. The increase of density induced negative buoyancy that created a downdraft, which was further increased by microphysical cooling, such as the evaporation of the rain, the melting of snow and hail, the accretion of rain by snow and rain, and the evaporation of liquid water from melting snow and hail (Proctor, 1988). From the precipitation-induced microburst, Proctor (1988) found that microbursts were primarily driven by cooling due to evaporation of rain and melting of the hail and that there are vortex rings that appear before and after the downdraft impinges on the ground, stretching out as they translate in the radial direction as the outflow propagates.

Other investigators (Lin et al., 2007; Mason et al., 2009; Vermeire et al., 2011a, 2011b; Oreskovic et al., 2018a) simulated downburst events using a subcloud model with a forcing cooling source (CS) to generate the negative buoyancy, instead of precipitation, as in Proctor’s (1988) simulations. The imposed forcing CS is the one developed by Anderson
et al. (1992), based on experience with full-cloud models which suggested that realistic outflows can be generated using a downdraft forcing field consisting of a simple space- and time-dependent cooling function which forces the model temperature field. The CS has an ellipsoidal geometric shape with horizontal half-widths of 1200 m and vertical half-width of 1800 m, and a forcing peak cooling rate of -0.052 K/s to approximate the structure of the downburst-producing thunderstorm (Straka & Anderson, 1993). This forcing model was then utilized in a sensitivity analysis to investigate the effects of the downdraft cooling rate and diameter on the strength of the outflow by Oreskovic et al. (2018a), which demonstrated that increasing the cooling rate intensity of the forcing CS significantly increases both the strength of the downdraft and the peak horizontal wind speed. The increase in strength is also observed when the diameter and the elevation of the CS are increased (Mason et al., 2009; Oreskovic et al., 2018a). Mason et al. (2009) investigated the effects of the CS diameter by varying it between 0.55 and 3.8 km. The results showed that increasing the CS diameter, the radial location of the peak radial wind speed increases but the magnitude of the radial peak speed remains the same (Mason et al., 2009).

Despite the successful downburst-producing thunderstorm simulations using full-cloud models and the in-depth studies of the downburst outflows using subcloud models, there has not been any study that attempts to match the results of the subcloud models with those from full-storm downburst simulations. To achieve this, a forcing CS of a specific template (shape and dimensions) needs to be developed for use in the subcloud model simulations. In analyzing the full-storm simulation data of Orf et al. (2012), Oreskovic et al. (2018b) suggested that the radial length scale of the downdraft column was about 650 m, and the centre of any equivalent forcing CS would be around 2500 m AGL, based on the radius of the downdraft column and the cloud base height, respectively. These suggestions were due to the lack of a defined source for the downdraft in the storm simulated (Oreskovic et al., 2018b). This chapter investigates the correct forcing CS template to produce a downburst outflow with similar characteristics and wind speed profiles (radial and temporal) observed in the downburst-producing thunderstorm by Orf et al. (2012, 2014).
5.2 Description of the numerical model

The numerical model used in this research is the latest version of the Cloud Model 1 (CM1), cm1r19.10. CM1 is scientifically defined as a three-dimensional, nonhydrostatic, nonlinear, time-dependent numerical model designed specifically for the simulation of ideal cases of atmospheric phenomena (Bryan, 2002). The model is nonhydrostatic because it takes into account the vertical acceleration observed in realistic thunderstorms. CM1 solves the large eddy simulation (LES) equations — the filtered Navier-Stokes equations — for the three spatially filtered orthogonal velocity (u, v, w), the non-dimensional pressure perturbations (\( \pi' \)), potential temperature perturbations (\( \theta' \)), and the non-dimensional mixing ratios of moisture variables (\( q_x' \)), where the subscript \( x = l \) denotes liquid, \( x = v \) denotes vapor, and \( x = i \) denotes ice. The derivative terms in the governing equations are discretized, and the 6th order diffusion scheme (\( k_{\text{diff}} = 0.040 \)) is used to solve the advection (spatial) derivatives, as recommended by Oreskovic et al. (2018a) because it removes the instabilities caused by the premature development of fluctuations in the temperature field observed in the 5th order scheme (Oreskovic, 2016). The 3rd order Runge-Kutta (RK3) time integration scheme is used to solve the temporal derivative terms. To solve the small-scale components that are not considered in the filtered equations, a subgrid-scale (SGS) turbulence closure based on Deardorff (1980) is used because it considers turbulence as anisotropic and unsteady, making it ideal for small grid resolution (Oreskovic et al., 2018a).

5.2.1 The governing equations of CM1 (Bryan, 2017)

The governing equations for velocity in CM1 are the filtered Navier-Stokes equations

\[
\frac{\partial u}{\partial t} + c_p \theta_p \frac{\partial \pi'}{\partial x} = \text{ADV}(u) + f v + T_u + D_u + N_u
\]  

(5.1)

\[
\frac{\partial v}{\partial t} + c_p \theta_p \frac{\partial \pi'}{\partial y} = \text{ADV}(v) - f u + T_v + D_v + N_v
\]  

(5.2)

\[
\frac{\partial w}{\partial t} + c_p \theta_p \frac{\partial \pi'}{\partial z} = \text{ADV}(w) + B + T_w + D_w + N_w
\]  

(5.3)
where $c_p$ is the specific heat of dry air at constant pressure, $f$ is the Coriolis parameter, which is only considered if Coriolis acceleration is taken into account, $\theta_\rho$ is the density potential temperature, and $u$, $v$, $w$, denote the filtered orthogonal velocity components in the $x$ (east-west), $y$ (north-south), and $z$ (vertical) directions, respectively. The D, N, and T terms represent the optional tendencies from other diffusive processes, the Newtonian relaxation (i.e., Rayleigh damping), and the tendency from sub-grid turbulence respectively. $B$ is the buoyancy due to the temperature difference between the forcing CS and the ambient. ADV is the advection operator, defined in CM1 for a variable $\alpha$ in the form:

$$ADV(\alpha) = \frac{1}{\rho_0} \left[ -\nabla \cdot (\alpha \rho_0 \vec{V}) + \alpha \nabla \cdot (\rho_0 \vec{V}) \right] \tag{5.4}$$

where $\rho_0$ is the base state density, $\nabla = \left( \frac{\partial}{\partial x}, \frac{\partial}{\partial y}, \frac{\partial}{\partial z} \right)$ is the gradient operator, and $\vec{V}$ is the velocity vector $(u, v, w)$. In cartesian coordinates, ADV $(\alpha)$ is given by

$$ADV(\alpha) = \frac{1}{\rho_0} \left[ -\frac{\partial (\alpha \rho_0 u)}{\partial x} - \frac{\partial (\alpha \rho_0 v)}{\partial y} - \frac{\partial (\alpha \rho_0 w)}{\partial z} \right. \tag{5.5}$$

$$+ \alpha \left( \frac{\partial (\rho_0 u)}{\partial x} + \frac{\partial (\rho_0 v)}{\partial y} + \frac{\partial (\rho_0 w)}{\partial z} \right) \right]$$

The buoyancy $B$ in the Equation (5.3) is given in terms of the density potential temperature $(\theta_\rho)$,

$$B = g \frac{\theta_\rho - \theta_\rho^0}{\theta_\rho^0} \tag{5.6}$$

where subscript ‘0’ denotes the base state, and $g = 9.81 \text{ m/s}^2$ is the gravitational constant. Considering a dry environment, the governing equation for non-dimensional pressure perturbations $(\pi')$ is the following:

$$\frac{\partial \pi'}{\partial t} = ADV(\pi') - \frac{R}{c_v} \pi (\nabla \cdot \vec{V}) \tag{5.7}$$
where $R$ is the gas constant for dry air, $c_v$ is the specific heat at a constant volume, and $\pi$ is the non-dimensional pressure.

The governing equation for the perturbation potential temperature ($\theta'$) is given by

$$\frac{\partial \theta'}{\partial t} = \text{ADV}(\theta) + T_\theta + D_\theta + N_\theta + \frac{1}{\pi c_p} \varepsilon + q(x, y, z, t) \quad (5.8)$$

where the term $\varepsilon$ denotes the dissipation rate associated with the increase in internal energy of the cooling source when kinetic energy is dissipated, and $q(x,y,z,t)$ denotes the spatial and temporal cooling source (CS) function (to be discussed in the next section).

The governing equations for the moisture components, $q_l$, $q_v$, $q_i$, are discussed in detail in section 2 in CM1 governing equations documentation (Bryan, 2002), so they are not presented here. The turbulent tendencies due to the small-scale turbulence, $T_u$, $T_v$, and $T_w$, in the Equation (5.1), (5.2), and (5.3) are formulated by the equations:

$$T_u = \frac{1}{\rho} \left[ \frac{\partial \tau_{11}}{\partial x} + \frac{\partial \tau_{12}}{\partial y} + \frac{\partial \tau_{13}}{\partial z} \right] \quad (5.9)$$

$$T_v = \frac{1}{\rho} \left[ \frac{\partial \tau_{12}}{\partial x} + \frac{\partial \tau_{22}}{\partial y} + \frac{\partial \tau_{23}}{\partial z} \right] \quad (5.10)$$

$$T_w = \frac{1}{\rho} \left[ \frac{\partial \tau_{13}}{\partial x} + \frac{\partial \tau_{23}}{\partial y} + \frac{\partial \tau_{33}}{\partial z} \right] \quad (5.11)$$

where $\tau_{ij}$ are the subgrid stress terms formulated by

$$\tau_{ij} \equiv -\rho u_i u'_j = 2\rho K_m S_{ij} \quad (5.12)$$

where $K_m$ is the viscosity and $S_{ij}$ is the strain tensor given by

$$S_{ij} = \frac{1}{2} \left[ \frac{\partial u_i}{\partial x_j} + \frac{\partial u_j}{\partial x_i} \right] \quad (5.13)$$

The turbulent fluxes for the potential temperature, $\theta$, is given by
\[ \tau_i^\theta \equiv \rho u_i' \theta' = -K_h \rho \frac{\partial \theta}{\partial x_i} \]  \hfill (5.14)

where \( K_h \) is turbulence diffusivity. The turbulent fluxes associated the moisture, \( \tau_i^q_i, \tau_i^q_v, \tau_i^q_i \) are discussed in detail by Bryan (2002).

\( K_m \) and \( K_h \) need to be determined via the method chosen when setting up CM1 for a given application. For the downburst simulation, the turbulent kinetic energy (TKE) subgrid-scale model is used to solve for \( K_m \) and \( K_h \), as discussed in the following section.

### 5.2.2 Subgrid-scale turbulence model

A turbulent kinetic energy scheme (TKE) is used as the subgrid-scale model to determine \( K_m \) and \( K_h \). The TKE scheme in CM1 is similar to that described by Deardorff (1980), where the eddy viscosity \( K_m \) and the eddy diffusivity \( K_h \) are determined from the relations

\[ K_m = c_m l e^2 \]  \hfill (5.15)

\[ K_h = c_h l e^2 \]  \hfill (5.16)

where \( c_m = 0.10 \) m in CM1 and \( e \) is the subgrid TKE, given by

\[ e = \frac{1}{2} u_i' u_j' \]  \hfill (5.17)

and the predictive equation for \( e \) is

\[ \frac{\partial e}{\partial t} = \text{ADV}(e) + K_m S^2 - K_h N_m^2 + \frac{1}{\rho} \frac{\partial}{\partial x_i} \left( 2\rho K_m \frac{\partial e}{\partial x_i} \right) - \varepsilon \]  \hfill (5.18)

where \( \varepsilon \) is dissipation, parameterized as

\[ \varepsilon = \frac{c_e e^2}{l} \]  \hfill (5.19)

\( S^2 \) is the deformation, defined by
\[ S^2 = 2S_{ij}S_{ij} \] (5.20)

\[ N_m^2 = \frac{g}{\theta_\rho} \frac{\partial \theta_\rho}{\partial z} \] (5.21)

The mixing length \( l \), \( c_h \), and \( c_e \) in the Equation (5.15) and (5.16) are formulated as

\[ l = \left( \frac{2}{3} \frac{e}{N_m^2} \right)^{\frac{1}{2}} \] (5.22)

\[ c_h = 1 + 2 \frac{l}{\Delta} \] (5.23)

\[ c_e = 0.2 + 0.787 \frac{l}{\Delta} \] (5.24)

where \( \Delta \) is the spatial filter size, which is defined as a function of the smallest three-dimensional sub-grid volume of the computational volume.

\[ \Delta = (\Delta x \Delta y \Delta z)^{\frac{1}{3}} \] (5.25)

### 5.2.3 The cooling source model

The cooler negatively-buoyant air that grows within the numerical domain and descends to the ground creating the downburst is governed by the forcing cooling source (CS) model by Anderson et al. (1992), commonly used in the simulation of downbursts employing subcloud models (Mason et al., 2009; Vermeire et al., 2011a,b; Oreskovic et al., 2018a,b). The space- and time-dependent forcing cooling function \( q(x,y,z,t) \) is designed to approximate the structure produced by the full-cloud model simulations by Straka and Anderson (1993), presented as a product of space and time functions, with the space structure function defined as one cycle of \( \cos^2(R) \), where \( R \) is the scaled radial position in
the ellipsoidal region (Figure 5.2) of half-widths \( h_x, h_y, \) and \( h_z \), bounded by \( R = 1 \) (Oreskovic et al., 2018a). \( R < 1 \) is the region inside and \( R > 1 \) is the region outside the ellipsoid.

\[
q(x, y, z, t) = \begin{cases} 
  g(t) \cos^2(0.5 \pi R) & \text{for } R < 1 \\
  0 & \text{for } R > 1 
\end{cases} \quad (5.26)
\]

The function \( g(t) \) is the growth of the cooling rate which is set to reach the peak value (\( q_{\text{max}} \)) after 120 s, remaining constant from 120 s to 720 s, then decreasing until reaching zero cooling rate at 840 s, remaining constant afterward (Figure 5.3).

\[
g(t) = \begin{cases} 
  -q_{\text{max}} \cos^2 \left[ \frac{\pi}{2(120)} \left( t - 120 \right) \right] & t \leq 120 \\
  -q_{\text{max}} & 120 < t \leq 720 \\
  -q_{\text{max}} \cos^2 \left[ \frac{\pi}{2(120)} \left( t - 720 \right) \right] & 720 < t \leq 840 \\
  0 & t > 840 
\end{cases} \quad (5.27)
\]

The non-dimensional scaled radius \( R \) is given by the relationship

\[
R = \sqrt{\left( \frac{x - x_0}{h_x} \right)^2 + \left( \frac{y - y_0}{h_y} \right)^2 + \left( \frac{z - z_0}{h_z} \right)^2} \quad (5.28)
\]

where \((x_0, y_0, z_0)\) is the spatial location of the ellipsoidal CS. \( h_x, h_y, \) and \( h_z \) are the half-widths of the ellipsoid with \( h_x, h_y \) (Orf & Anderson, 1999). The centre of the CS is located at \( h_c \), and at the centre of the computational domain.

![Figure 5.2: Representation of the ellipsoidal forcing cooling source in the computational domain.](image)
Methodology

The simulations are carried out in Shared Hierarchical Academic Research Computing Network (SHARCNET) using CM1 (Bryan, 2002) with a forcing cooling source model. The computational domain has a height of 4 km and a square base of a side 9.6 km, creating a volume of 9.6 km $\times$ 9.6 km $\times$ 4 km. The dimensions of the domain were selected so that domain independence is achieved. The horizontal mesh grid spacing has the size $\Delta x = \Delta y = 10$ m, which gives grid-independent results, with a mean difference in velocity of 0.09% when compared with a very refined mesh having $\Delta x = 6$ m (Oreskovic, 2016). For the vertical mesh, a mesh refinement was applied by using a stretching mesh based on Wilhelmson and Chen (1982). The first grid point above the ground is at $\Delta z = 1$ m, stretching to $\Delta z = 50$ m at the top of the domain giving 160 horizontal planes. This generates a total of 147,456,000 grid points for the mesh in the full domain. The boundary conditions are chosen so that the downburst is simulated in conditions similar to those observed in actual downburst events. The lateral sides of the domain are treated as open-radiative surfaces to allow the flow to enter and exit the domain. Similar to previous work (Mason et al., 2009; Vermeire et al., 2011a,b; Oreskovic et al., 2018a,b), the bottom surface is treated as a semi-slip surface with the surface roughness set to $z_0 = 0.10$ m, equivalent to short-crop terrain (Vermeire et al., 2011a). The heat fluxes between the bottom surface
and the air are not included since there is no difference in temperature. The top surface of the domain is set as a free-slip condition. The atmospheric conditions are the same as the atmospheric sounding observed by Brown et al. (1982), which represents conditions leading to the formation of dry downbursts over the High Plains, USA (Orf et al., 2012). A time step of $\Delta t = 0.05$ s with 10 acoustic sub-steps was used to maintain computational stability while achieving time-step independence (Oreskovic, 2016), and all the simulations were run for 20 min, enough time to allow for the decay of the vortices in the simulated downburst outflows. Each simulation took approximately 6 hours in real-time.

5.3.1 The circumferential averaging approach

Processing the massive 3D velocity data is computationally expensive, and a huge amount of memory is required. Orf et al. (2012, 2014) developed the circumferential averaging approach (Figure 5.4) to reduce computational cost while preserving the peak radial outflow speed and the location. The approach converts the flow velocity ($u$, $v$, $w$) from three-dimensional cartesian coordinates ($x$, $y$, $z$) into a three-dimensional cylindrical coordinate ($r$, $\theta$, $z$), resulting in the velocity vector ($u_r$, $u_\theta$, $w$) where $u_r = \sqrt{u^2 + v^2}$. Since the flow is mostly linear (no swirling like in tornadoes) the velocity in the azimuthal direction $u_\theta$ is negligible ($u_\theta = 0$). The centre of the main downburst is found by identifying the point of divergence of the horizontal wind vectors. Then, at each imposed constant radial distance ($r$) from the impingement and altitude ($z$), the radial ($u_r$) and vertical ($w$) wind speeds are spatially averaged around a circumference of the circle of radius $r$ (Figure 5.4) (Orf et al., 2014). As a result, the asymmetric downburst outflow is transformed to symmetric flow around the circumference of radius $r$, and the data are independent of the azimuth angle $\theta$ ($0 < \theta < 2\pi$), thereby reducing the three-dimensional data into a two-dimensional data set ($r$, $z$), with the velocity vector ($u_r$, $w$). Orf et al. (2014) demonstrated that the downdraft from the full-storm simulation had an approximately circular base just a few metres ($z < 250$ m) above ground level (ABL). Therefore, the use of the circumferentially-averaged velocity ($u_r$, $w$) to analyze the downburst outflow near the ground is justifiable, and it has been successful in data analysis, despite eliminating some of the downdraft primary and secondary vortex rings (Orf et al., 2012).
5.4 Numerical simulation data

In the present study, CS simulations at various forcing peak cooling rates ($q_{\text{max}}$) and CS dimensions ($h_x$, $h_y$, $h_z$) (Figure 5.2) were carried out in SHARCNET using cloud model CM1 (Bryan, 2002), with a forcing ellipsoidal CS similar to that of Anderson et al. (1992), but with the horizontal width ($h_x = h_y$) and the vertical width ($h_z$) changed to produce downburst events with the same characteristics — radial and temporal velocity profile, and the downdraft column diameter — as those produced in the downburst-producing thunderstorm by Orf et al. (2012, 2014). The naming format of the simulations is CS-$q_{\text{max}}$-$h_x$-$h_y$-$h_z$-$h_c$, where CS denotes that the simulation was conducted using a forcing CS to generate the downdraft, and $h_c$ is the vertical location of the centre of the CS. The peak cooling rate and the widths of the CS were selected so that the peak circumferentially averaged radial wind speed generated, and the corresponding radial location is approximately equal to those produced in full-storm simulations by Orf et al. (2012, 2014), which is 17 m/s and 1500 m respectively. Using $q_{\text{max}} = 0.08$ K/s, $h_x = 1200$ m, $h_z = 1800$ m, $h_c = 2000$ m, which are the parameters for the baseline simulation in subcloud models.
(Anderson et al., 1992; Vermeire et al., 2011a; Oreskovic et al. 2018a), led to peak circumferentially averaged wind speed higher than the 17 m/s observed in full-cloud model simulation by Orf et al. (2012, 2014). Since the peak cooling rate is directly proportional to the peak radial speed and the CS parameters (h_x, h_y, h_z, h_c) are linearly proportional to the peak radial location (Oreskovic et al., 2018a), the peak cooling was reduced to produce the correct peak circumferentially averaged wind speed and the CS geometrical parameters were reduced to achieve the desired peak radial location. The appropriate q_max obtained ranged from 0.03 K/s to 0.05 K/s, which were combined with the appropriate CS parameters (h_x, h_y, h_z, h_c) to generate the correct peak speed at the radial location near 1500 m. Mason et al. (2009) and Oreskovic et al. (2018a) showed that the bigger the downdraft diameter, the larger is the radial outflow depth. Based on that, the horizontal width (h_x, h_y) was increased up to 1600 m, combined with a vertical width (h_z) and vertical location of the CS centre (h_c) through trial and error, to achieve the correct radial peak speed location. A further increase of the horizontal width (h_x, h_y) seems unreasonable because most of the downbursts observed in actual events such as those in JAWS have a radius ranging from 500 m to 1500 m (Hjelmfelt, 1988; Orf et al., 2012). Table 5.1 shows the CS simulations analyzed in this chapter, which are those that best matched the criteria described above.

Table 5.1: Summary of the simulations carried out in CM1.

<table>
<thead>
<tr>
<th>Simulations in CM1</th>
<th>q_max (K/s)</th>
<th>h_x, h_y (m)</th>
<th>h_z (m)</th>
<th>h_c (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>CS-003-1500-1000-1200</td>
<td>0.03</td>
<td>1500</td>
<td>1000</td>
<td>1200</td>
</tr>
<tr>
<td>CS-003-1500-1000-1500</td>
<td>0.03</td>
<td>1500</td>
<td>1000</td>
<td>1500</td>
</tr>
<tr>
<td>CS-003-1600-1200-1400</td>
<td>0.03</td>
<td>1600</td>
<td>1200</td>
<td>1400</td>
</tr>
<tr>
<td>CS-005-1600-1200-1400</td>
<td>0.05</td>
<td>1600</td>
<td>1200</td>
<td>1400</td>
</tr>
<tr>
<td>CS-004-1500-1200-1700</td>
<td>0.04</td>
<td>1500</td>
<td>1200</td>
<td>1700</td>
</tr>
</tbody>
</table>
5.5 Results and discussion

This section presents and discusses the results of the CS model simulations performed. The results are compared to full-cloud model simulations by Orf et al. (2012, 2014).

5.5.1 Variation of the outflow wind speed with the radial distance at the time the peak outflows radial wind speed occurs.

In order to match the peak outflow radial wind speed magnitude ($u_r$) and the corresponding radial location ($r_{\text{max}}$) of the CS simulations with the downburst-producing thunderstorm, the simulations in Table 5.1 were conducted and analyzed. Figure 5.5 shows the variation of the circumferentially-averaged radial speed ($u_r$) with the radial location ($r$) at the height and time ($t$) that the peak radial speed occurs, with time being measured from the start of the simulation. All the simulations seem to follow the same radial wind speed profile pattern at the time each simulation reaches the peak $u_{r,\text{max}}$. The pattern can be described as follows: at those instants, the radial wind speed increases linearly from the impingement location ($r = 0$ km) to the radial location of approximately $r = 0.4$ km, changing shape to a parabolic with some perturbances until reaching the peak speed at the radial location near $r = 1.5$ km (the black dashed line in Figure 5.5). The radial speed starts then decreasing with some perturbances near the peak speed, which disappears downstream as the radial wind speed drops to zero since the atmospheric ambient is quiescent (Figure 5.5). Perturbances or variabilities along the profiles are expected since these profiles are instantaneous and not time-averaged. A peak radial wind speed higher than 20 m/s is obtained when the peak cooling rate is higher than 0.04 K/s as seen in Figure 5.5, regardless of the CS parameter ($h_x, h_y, h_z, h_c$) combination. This is reasonable since the peak cooling rate is linearly proportional to the peak speed as asserted by Oreskovic et al. (2018a). The vertical location of the centre of the forcing CS ($h_c$) also contributed to the increase of the peak radial wind speed and had to be reduced along with the peak cooling rate. The height was reduced from $h_c = 1700$ m (with $q_{\text{max}} = 0.04$ K/s) to $h_c = 1400$ m (with $q_{\text{max}} = 0.03$ K/s) to reduce the peak speed. The increase of the horizontal width of the forcing CS ($h_x = h_y$) increased the outflow radial peak speed location to approximately $r = 1.5$ km, which is the radial peak location observed in the full-storm simulation (Orf et al., 2012, 2014). Horizontal width from $h_x = h_y = 1500$ m to 1600 m resulted in peak radial
distances from 1.25 to 1.5 km, which correspond to a maximum percentage difference of 13.3% when compared with the $r = 1.5$ km from full-storm simulation. The increase of the CS vertical width ($h_z$) also increased the radial peak speed, with better effects when it ranges from 1000 m to 1200 m. From Figure 5.5, the simulations with $0.03 \text{ K/s} \leq q_{\text{max}} \leq 0.05 \text{ K/s}$, where $1500 \text{ m} \leq h_x = h_y \leq 1600 \text{ m}$, $1200 \text{ m} \leq h_c \leq 1400 \text{ m}$, and $1000 \text{ m} \leq h_Z \leq 1200$ are the those that best match the peak radial speed in the full-storm simulations (Orf et al., 2012, 2014) and the corresponding radial location. It should be noted that the centre of the forcing CS ($h_c$) is between 1200 m and 1400 m, which is less than the 2500 m estimated by Oreskovic et al. (2018b) for the vertical location of the source generating the downdraft in the full-cloud model simulations. At $h_c = 2500$ m, CS simulations generated peak circumferentially-averaged radial wind speed higher than 17 m/s, which is observed in full-storm simulations by Orf et al. (2012), even when the peak cooling rate was as low as $q_{\text{max}} = 0.03 \text{ K/s}$.

![Figure 5.5: Radial variation of the circumferentially-averaged wind speed at the height of the peak wind speed.](image)
In Figure 5.6, the CS simulations that best match the peak wind speed of 17 m/s and corresponding radial location of 1.5 km are compared with the full-CM circumferentially averaged radial wind speed profile at the height and time (606 s, 628 s) of the peak radial speed (Orf et al., 2012, 2014). It is observed that the CS simulations’ peak speeds have percentage error differences ranging from 2.2-9.3% when compared with the full-CM peak radial speed at 606 s. When comparing with the full-CM peak radial speed at 628 s, the magnitudes differ with a percentage differences ranging from 4.5-6.1%. These differences are acceptable since they are less than 10%. Also, the corresponding peak radial speed locations (r_{\text{max}}) differ, with the best CS simulations having r_{\text{max}} = 1.25 km and the full-CM at 606 s having r_{\text{max}} = 1.5 km, which corresponds to a difference of 22.2%. A much higher percentage difference, 32%, is obtained when comparing with full-CM at 628 s. This implies that the horizontal width (h_x = h_y), the peak cooling rate (q_{\text{max}}), or the CS centre altitude (h_c) should be further increased. However, increasing h_c or q_{\text{max}} resulted in a peak radial speed of about 21 m/s, which corresponds to a 20% and 24% percentage difference when compared with the peak radial speed magnitudes from the full-CM simulation at 606 s and 628 s, respectively. Further increase of h_c = h_y does not seem reasonable since downdraft with a radius higher than 1600 m would be generated, which is uncommon. The maximum radius of downbursts simulated or observed thus far is 1500 m (Hjelmfelt, 1988; Orf et al., 2012). Since peak wind loads are of more interest due to the effects on infrastructures, a smaller percentage difference in peak speed was prioritized, and the three simulations in Figure 5.6 are rendered as the best match. Figure 5.6 shows that the CS simulations decay to zero after reaching the peak wind speed, whereas the full-CM simulations do not. This is due to the environmental wind caused by an earlier downdraft prior to the downburst, which does not occur in CS simulations (Oreskovic et al., 2018b). The same effect is observed at the centre of the downburst r = 0 km, where the radial speed is nonzero in the full-CM simulations (Orf et al., 2012, 2014).
Figure 5.6: Comparison of the circumferentially-averaged radial wind speed between CS simulations and full-CM simulation by Orf et al. (2012, 2014) at the height and time the peak radial wind speed occurs.

5.5.2 Temporal variation of the circumferentially-averaged radial wind speed ($u_r$) and the instantaneous horizontal wind speed ($V_H$)

Figure 5.7 shows the time history of the peak circumferentially-averaged radial wind speed ($u_r$) at the corresponding radial location, for each CS and full-CM simulation. The circumferentially-averaged radial speed of the full-storm simulation by Orf et al. (2012) at $r = 1.5$ km, was presented by Oreskovic et al. (2018b). It can be seen that the peak radial speed magnitudes are approximately equal, with percentage differences ranging from 1 to 2%. At $t = 0$ s, $u_r = 2$ m/s in the full-CM simulation (Figure 5.7), which is the environmental wind resulting from earlier downdrafts or updrafts that were observed in the domain before the downburst (Orf et al., 2012; Oreskovic et al., 2018b). However, it should be noted that this radial comparison is carried out when the start of the downdraft (around 3000 s) at the
full-CM simulation, at about 3300 m, is considered as $t = 0$ s, whereas $t = 0$ s is the start of the simulation for the CS simulations. The downdraft in the CS simulations is observed at $t = 130$ s, implying that the CS simulations should be compared with the full-CM simulations for the time $(t - 130)$ s. However, Figure 5.7 shows the radial speed ($u_r$) of downdraft in the full-CM simulations start much later than in CS simulations, about 150 s. This results in a total delay of about 280 s.

This delay suggests that the forcing CS function $q(x,y,z,t)$ should be composed in such a way that it accounts for the time delay, causing the CS downdraft to begin 280 s earlier than the current time if it is to produce the same circumferentially-averaged profile, peak radial speed, and time history that the downburst-producing thunderstorms. This would also allow the carryout of longer CS simulation without affecting the peak wind speed and the respective radial location since they are only dependent on the CS size, peak cooling rate, and the initial height AGL.

![Figure 5.7](image)

**Figure 5.7:** Temporal variation of the peak circumferentially-averaged radial speed at the corresponding radial location: $r = 1.2$ km (CS simulations) and $r = 1.5$ km (full-CM simulation).

Without removing the delay, it is difficult to argue that the circumferentially-averaged radial wind speed profile from the CS likens to that of the full-CM simulation at the location and time the peak $u_r$ occurs in each simulation. Comparing the time difference ($T$) between
the rise and fall to the half peak $u_r$ value (Figure 5.8), it is seen that the one observed in the CS simulations is nearly double to that of the full-CM simulations. However, even removing the delay may not result in a significant change because it may result in smaller $T_1$ but large $T_2$ since the full-CM circumferentially-averaged radial speed decays faster (Oreskovic et al., 2018b).

Figure 5.8: Time difference ($T$) between the rise and fall to the half peak of circumferentially-averaged radial wind speed.

Due to the differences observed in the comparison with the circumferential-averaged profile (Oreskovic et al., 2018b), more comparisons are carried out using instantaneous horizontal wind speed in the x-direction ($V_H$) from the full-CM downburst simulation by Orf et al. (2012), given by $V_H = \sqrt{u^2 + v^2}$, where $u$ and $v$ are instantaneous cartesian velocity components in the x- and y-direction respectively.

The height at which the peak $V_H$ occurs in the CS simulations ranges from 18 to 19 m AGL, which is very close to the 19 m AGL observed in location B of the full-storm downburst by Orf et al. (2012). Figure 5.9 shows the time history of the instantaneous horizontal wind speed ($V_H$) at $z = 19$ m AGL and the location at which the peak $V_H$ occurs for each CS simulation, as well as a comparison with location B from the full-CM simulation by Orf et al. (2012). A percentage difference ranging from 2 to 12% is observed
when comparing the peak $V_H$ between the CS simulations and the full-CM location B until 590 s, with the CS peak $V_H$ ranging from 20 m/s to 26 m/s. As seen in Figure 5.9, The instantaneous horizontal wind speed ($V_H$) at location B of the full-CM downburst starts growing steadily before starting to fluctuate rapidly after 320 s, with $V_H$ seen as transient gusts by the spikes on the time-series graphs that last only a few seconds. On the contrary, the CS simulations exhibit fewer fluctuations resulting in a smooth line that coincides with the full-CM location B smaller peak wind gusts until 590 s (Figure 5.9). The less fluctuation in CS simulations is probably due to the lack of the microphysics parameterizations which accounts for the complexities associated with precipitation descending to the domain, which is observed in full-CM downburst (Orf et al., 2012). After 590 s, location B continues fluctuating and reaches the peak horizontal wind gust of 37 m/s at 628 s, which is not captured by the CS simulations. The best agreement in the temporal profile is observed between CS-003-1500-1000-1200 and full-CM location B as shown in Figure 5.9.

Figure 5.9: Temporal variation of the instantaneous horizontal wind speed ($V_H$) at the location and height $z = 19$ m AGL corresponding to the peak $V_H$. Comparison with the location B of the full-CM downburst Orf et al. (2012).
Again, the time history in Figure 5.9 is carried out by considering the start of the downdraft in the full-CM simulation, which occurs around 3000 s, as \( t = 0 \) s when compared with the CS simulations. That is, \( t = 0 \) s is the start of the CS simulations the start of the downdraft at a height of 3300 m for the full-CM simulation. Since the complex full-CM simulation (Orf et al., 2012) takes 3000 s for the downdraft to form and at a height nearly double the forcing CS centre height, it is reasonable to consider \( t = 3000 \) s as 0 s for meaningful comparison with the CS simulations.

### 5.5.3 Vertical velocity profile

A comparison of the vertical profile between the CS simulations and the full-CM simulation downburst by Orf et al. (2012) is important to understand how the CS simulations match the speed profile of the more realistic downburst events. Figure 5.10a shows the comparison of the circumferentially-averaged velocity \( (u_r) \) profile between the CS simulations and the full-CM simulations. It can be seen that the vertical profiles of the CS decay to zero much faster than the full-CM simulations. At the height \( z = 400 \) m, the CS simulations have zero \( u_r \), when it is around 5 m/s in the full-CM simulations. As explained before, this is due to the environmental wind, updraft, and downdraft air that occur during the thunderstorm simulation in the full-CM before the downburst occurs (Orf et al., 2012).

The peak radial wind speed is observed at \( z = 50 \) m in the full-CM simulation at \( t = 606 \) s, and at \( z = 19 \) m at \( t = 628 \) s, whereas the peak \( u_r \) height in the CS simulation ranged from 15 to 22 m. This shows that better matching of peak altitude is obtained between the CS simulations and full-CM at \( t = 628 \) s, with percentage differences ranging from 15 – 24%. This discrepancy is due to the lower resolution observed near the ground in the full-CM simulations (Figure 5.10b). For example, the first grid point in the present CS simulation is at 1 m, whereas it is at 5 m in the full-CM simulation (Orf et al., 2012). This shows that subcloud models have better near-ground resolution compared to full-cloud models, as asserted by Orf (1997).
Figure 5.10: Vertical profile of the radial wind speed at the time and radial location the peak radial wind speed occurs. Comparison between CS and Full-CM downburst simulation. a) 0 – 500 m. b) 0 – 125 m.
The discrepancies in the peak height and the vertical profile shape were expected due to the poor agreement in the temporal radial wind speed profile as discussed previously and shown in Figure 5.8 and Figure 5.9. The profile from the full-CM simulation at \( t = 608 \) s resembles more to those in CS simulations in terms of the radial wind speed increase behaviour: increases from \( z = 0 \) m until it reaches the peak height and then decreases (Figure 5.10). However, the full-CM simulation profile at \( t = 628 \) s seems to remain constant after reaching the peak \( u_r \) from 19 to 125 m, then starts decreasing (Figure 5.10).

The resemblance observed between the CS simulation and the full-CM simulation at \( t = 608 \) s shows that the CS model can simulate downbursts that resemble the more realistic full-scale downburst produced by the full-CM simulations. However, the lack of hydrometeors (precipitation and cloud) in the CS model limits the CS simulation of downbursts since the short-time spike wind gusts observed in realistic events are not well captured. In addition, the CS model generates downburst events with a high degree of symmetry (axisymmetric), whereas most of the realistic events are asymmetric. Nevertheless, a better match between CS and the full-CM simulation – with smaller percentage differences in peak magnitudes, peak radial distance, and peak height – can be achieved if the forcing CS geometrical parameters are in the appropriate range. The centre of the CS should be anywhere between 1200 and 1700 m, and the horizontal with from 1500 to 1600 m. A further increase could be made to match \( r_{\text{max}} \) without affecting the magnitude of \( u_{r_{\text{max}}} \). The forcing CS function should be modified to include the time delay, of about 280 s, that is before the downdraft \( u_r \) start increasing in the full-CM simulation, and the forcing peak cooling rate should be higher than 0.03 K/s. It should be noted that the environmental conditions should be the atmospheric sounding from a realistic downburst event. Since most sounding have fewer data from 0 to 4.5 km (top of the domain), extrapolation and interpolation should be used to find enough data points (same as the vertical mesh resolution) to have the full approximate sounding near the ground.
5.6 Conclusions

Numerical simulations using cloud model 1 (CM1) (Bryan, 2002) with a forcing ellipsoidal CS by Anderson et al. (1992) are carried out to investigate the CS template able of producing downburst with the same characteristics and wind speed profile as those observed in a downburst-producing thunderstorm (Orf et al., 2012). Comparing the peak circumferentially-averaged radial wind speed ($u_r$), it is found that the CS simulations peak radial wind speeds have percentage error differences ranging from 2.2 - 9.3% when compared with the full-CM peak radial speed at 606 s, and 4.5 - 6.1% when compared with the full-CM peak radial speed at 628 s. These differences, which can be considered less significant since are less than 10%, are achieved when the forcing CS has adequate dimensions ($h_x$, $h_y$, $h_z$), cooling rate, and the base height from the ground ($h_c$): 1500 m ≤ $h_x = h_y$ ≤ 1600 m, 1000 m ≤ $h_z$ ≤ 1200 m, peak cooling rate $q_{max}$ ≥ 0.03 K/s, located at 1200 m ≤ $h_c$ < 1700 m. However, the corresponding peak radial speed locations ($r_{max}$) differ, with the best CS simulations having $r_{max} = 1.25$ km and the full-CM at 606 s having $r_{max} = 1.5$ km, which corresponds to a difference of 22.2%, and a much higher percentage difference, 32.0%, is obtained when comparing with full-CM at 628 s.

The temporal profile of the instantaneous horizontal speed ($V_H$) observed in CS simulations is compared with that obtained in the full-CM location B (Orf et al., 2012). A percentage difference ranging from 2 to 12% was observed when comparing the peak $V_H$ until 590 s, with the CS peak $V_H$ ranging from 20 to 26 m/s. However, full-CM fluctuates rapidly after 320 s, with $V_H$ seen as transient gusts by the spikes on the time-series graphs that last only a few seconds, whereas the CS simulations exhibit fewer fluctuations resulting in a smooth line that coincides with the full-CM location B smaller peak wind gusts until 590 s.

Downburst events are complex and simpler CS models alone cannot replicate all the complexities from full-CM simulations and observed downbursts. This was proved by the poor agreement in the vertical and temporal wind speed profile shape between the CS simulations and the full-CM locations of strong instantaneous horizontal wind speed (Orf et al., 2012). The lack of hydrometeors limits CS model simulations so it is recommended that future simulations include precipitation for better results.
5.7 References


Chapter 6

6 Discussion, conclusion, and recommendations

This chapter discusses the findings of this research (Chapter 3, 4, and 5), and presents the conclusion of this work. Recommendations for future studies are also presented.

6.1 Discussion

6.1.1 Implementation of the Lundgren et al. (1992) scaling parameters for CS model.

The application of the Lundgren et al. (1992) scaling parameters (length $R_0$, time $T_0$, velocity $V_0$) for CS simulations has been investigated in Chapter 3 of the current work. The scaling parameters are employed to scale downburst events simulated with an ellipsoidal CS of geometric parameters $h_x = h_y = 1200$ m, $h_z = 1800$ m, $h_c = 2000$ m, in a quiescent environment with a lapse rate of $9.80$ K/km. These geometric parameters, $h_x = h_y$ (horizontal half-widths), $h_z$ (vertical half-width), and $h_c$ (CS centre height AGL), are the same as the baseline case simulation in previous work (Anderson et al., 1992; Vermeire et al., 2011a, Oreskovic et al., 2018a). The intensity of the downdraft, quantified by the magnitude of the peak cooling rate ($q_{\text{max}}$) of the CS, is varied between $0.04$ and $0.08$ K/s while other parameters are maintained constant. It was found that the Lundgren et al. (1992) scaling parameters work well for CS simulations. The resulting scaled temporal profile of the peak radial wind speed collapsed into a single curve, with the percentage deviation from the mean (RMS) less than 10%. This resulted in a non-dimensional peak radial wind speed of $u_{r,\text{max}}/V_0 = 3.25$, occurring at $t/T_0 = 4.0$. The collapse of the data into a single curve was also observed at different non-dimensional radial locations $r/R_0$, all with RMS less than 10%. This shows that the radial wind speed profile of downbursts of different intensities are similar under the same environmental lapse rate (ELR). Comparison with experimental (Graat, 2020; Jariwala, 2021) and numerical work (Oreskovic et al., 2018a) showed that the scaled profiles preserved the profile shape and the height where the peak radial wind speed occurs. In addition, the vortex rings obeyed the scaling laws since, when vortex rings at $t/T_0 = 4.0$ were identified using the Q criterion (Chen et al., 2015), where the $QR_0^2/V_0^2$ was the scaled Q-value, resulted in a good scaling
of the vortex rings. The same was observed in the scaled circulation magnitude of the strong primary vortex rings near the ground. This shows that the scaling parameters (Lundgren et al., 1992) are not solely limited to liquid release models.

This achievement was possible due to the suitable approach employed to compute the non-dimensional density difference $\Delta \rho/\rho$, which is difficult to solve in CS simulations since the downdraft density varies spatially and temporally. This approach showed that the radius of the downdraft is less than the radius of the forcing CS ($h_x = h_y$), which was found to be 62.2% ($\beta = 62.2\%$) of the CS radius ($h_x = h_y$). The approach involved solving for the spatially-averaged densities inside and outside the CS with the limits set by the radius of the downdraft. The temporal profile of $\Delta \rho/\rho$, which quantifies buoyancy, showed that the increase of buoyancy in the CS until reaching the peak $\Delta \rho/\rho$ is similar regardless of the peak cooling rate of the CS. These findings aid in the understanding of the CS downdraft evolution in terms of buoyancy and cooling rate evolution until the vertical motion is detected.

6.1.2 The effects of environmental conditions on downburst events

The effects of environmental conditions on downburst outflows were investigated using a CS model (Anderson et al., 1992) in Chapter 4. Due to the lack of precipitation in subcloud models, this work focused on the environmental lapse rate (ELR) effects (6.76, 7.76, 8.26, and 9.80 K/km) on the downburst baseline case: $h_x = h_y = 1200$ m, $h_z = 1800$ m, $h_c = 2000$ m. Two peak cooling rate cases ($q_{\text{max}}$) were analyzed: 0.04 K/s and 0.08 K/s. The lapse rate values chosen were the same as those used in previous work (Orf, 1997). This work carried out an in-depth quantitative analysis and found out that downburst events with lower peak radial wind speed are produced when ELR is less than the dry adiabatic lapse rate (9.80 K/km). There was a 20% decrease in the peak radial wind when the environmental lapse was decreased from 9.80 K/km to 7.76 K/km, for $q_{\text{max}} = 0.08$ K/s. The CS simulations produced peak radial wind altitudes that were in the range of the downbursts simulated by Hjelmfelt (1988), which were based on a real event in Colorado. The highest vertical peak wind speed location was observed when ELR = 9.80 K/km, 150 m AGL.
Also, a delay in the downdraft development was observed, which was reflected in the downburst radial outflow evolution. Due to this, the outflow reached the peak radial wind speed and dissipation much later when the ELR < 9.80 K/km. It was also observed that the structure of the downdraft and the outflows did not change regardless of the ambient lapse rate if the intensity of the downburst was high enough so that the downdraft would reach the ground still negatively buoyant. A peak cooling rate of 0.08 K/s produced a downdraft with the same structure regardless of the ELR. However, when decreased to 0.04 K/s, the structure changed, with the outflow being warmer than the environment. This finding shows that the downburst structure does not stay the same regardless of the ELR, as stated in previous work (Mason et al., 2009). Finally, The Lundgren et al. (1992) scaling parameters introduced and discussed in Chapter 3, were employed to scale CS simulations when the ELRs are different. Results showed that the peak radial wind speed profiles are not similar when the ELR is less than the dry adiabatic lapse rate (9.80 K/km). This non-similarity is observed due to the heat gained by the downdraft before impinging on the ground when ELR < 9.80 K/km.

6.1.3 Investigation of a cooling source template that produces downburst outflows similar to those produced by cloud models.

The correct CS templates able of producing downbursts that are comparable with the more realistic downburst events by full-cloud models such as those by Orf et al. (2012, 2014) are investigated in Chapter 5 of the current work. The CS model by Anderson et al. (1992) is employed to carry out the simulations. Through the trial-and-error method, several CS simulations at different CS geometric parameters \( (h_x = h_y, h_z, h_c) \) and peak cooling rates \( (q_{\text{max}}) \) are conducted to find those that have a similar profile, peak radial wind speed \( (u_r = 17 \text{ m/s}) \), and the corresponding peak radial location \( r = 1.5 \text{ km} \), to the downburst-producing thunderstorm by Orf et al. (2012, 2014). The environmental conditions at which these simulations are carried out are the atmospheric sounding by Brown et al. (1982), which were used in the full-storm simulations (Orf et al., 2012, 2014). It was found that the CS simulation that best generates downbursts that resemble the downburst-producing thunderstorm by Orf et al. (2012, 2014), have the forcing CS of geometric parameters and forcing peak cooling rate in the following intervals: \( 1500 \text{ m} \leq h_x = h_y \leq 1600 \text{ m} \), \( 1000 \text{ m} \)
≤ h_c ≤ 1200 m, 1200 m ≤ h_c < 1700 m, q_{max} ≥ 0.03 K/s. Percentage differences less than 10% were obtained when comparing the magnitude of the peak circumferentially-averaged radial wind speed (u_r) of the CS simulations with the full-CM simulation by Orf et al. (2012, 2014). It was found that the CS simulations’ peak radial speeds have percentage error differences ranging from 2.2 - 9.3% when compared with the full-CM peak radial speed at 606 s, and 4.5 - 6.1% when compared with the full-CM peak radial speed at 628 s. However, the corresponding peak radial speed locations (r_{max}) differ, with the best CS simulations having r_{max} = 1.25 km and the full-CM at 606 s having r_{max} = 1.5 km, which corresponds to a difference of 22.2%, and a much higher percentage difference, 32.0%, is obtained when comparing with full-CM at 628 s. Poor agreement in the vertical and temporal radial wind speed profile shape was observed, with CS simulations decaying faster than the full-CM simulations.

### 6.1.4 Contributions to the field.

The current work has made significant contributions to the study of downburst events with cloud models, by showing the application of the scaling parameters used in liquid release experiments (Lundgren et al. 1992) for CS simulations in the same and different environmental lapse rate conditions. This will aid in the comparison of CS simulation with liquid model experiments. Also, it was shown that CS models can simulate downburst events with similar characteristics – velocity profile, peak radial wind speed, and the corresponding vertical and radial locations – as the downburst-producing thunderstorm simulations (Orf et al., 2012), which are more realistic. The right CS template and the peak cooling rate for the simulations have been identified and will serve as a guide for more realistic simulations using the CS model in the future.

### 6.2 Conclusion

This research investigated downburst events using cloud model 1 (CM1) (Bryan, 2002; Bryan & Fritsch, 2002) with a forcing cooling source (CS) of ellipsoidal shape (Anderson et al., 1992) to induce negative buoyancy and force the downdraft. This research aimed at filling gaps in the current knowledge and adding to our understanding of the downburst outflows by investigating the implementation of the Lundgren et al. (1992) scaling
variables for CS simulations, the effects of the environmental lapse rate on downburst events, and the CS template that generates downburst events comparable to the more realistic downburst produced by full-cloud model simulation. The findings discussed in this concluding chapter showed that the objectives of this research have been met, and the author hopes that these findings will make a significant impact and advance on downburst investigations.

6.3 Recommendations

Despite the findings mentioned, there were some limitations due to the numerical model used, and some areas identified that need further exploration. Therefore, for future studies, the following are recommended:

1) A subcloud model that includes precipitation should be used for more accurate results when studying the effects of environmental conditions on downbursts. Environmental lapse rate alone cannot account for all environmental conditions. Srivastava (1985) showed that precipitation and mixing of environmental air, which are not considered in this study since the subcloud model used is completely dry, also contribute to the environmental conditions. This will aid in advancing research on downbursts using subcloud models that include precipitation, which has only been done by a few researchers (Srivastava, 1985, 1987; Proctor, 1988) so far.

2) The sensitivity analysis of $\Delta \rho/\rho$ should be performed for forcing CS with dimensions different from the baseline case ($h_x = h_y = 1200$ m, $h_z = 1800$ m). This research would be useful in analyzing the variation of the region of integration for forcing CS of different sizes, as well as how the value of $\beta$ varies.

3) The application of the scaling parameters (Lundgren et al., 1992) to wet downburst simulations should be investigated since the current work is limited to dry downbursts. This would aid in understanding the effects of precipitation on the scaling parameters.
6.4 References


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