THE EFFECTS OF ENTRAINMENT IN THE DEVELOPING AND ROTATING STAGES OF SUPERCELL THUNDERSTORMS

BY

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THESIS

Submitted in partial fulfillment of the requirements for the degree of Master of Science in Atmospheric Sciences in the Graduate College of the University of Illinois at Urbana-Champaign, 2018

Urbana, Illinois

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ABSTRACT

Entrainment, the process by which turbulent clouds introduce dry air from outside the cloud inward via overturning eddies at the cloud edge, can decrease the cloud buoyancy, and the water and/or ice mass it contains, limiting both cloud and precipitation development. Numerous studies have shown that growing cumulus clouds entrain air primarily as a result of the overturning thermal circulation near their tops, but have focused upon cumuli in environments with minimal vertical wind shear. Little attention has been given to investigating the entrainment into developing thunderstorms growing in environments with strong vertical wind shear, or to how rotating updrafts in some thunderstorms (i.e. supercells; produced in environments with specific characteristics of the vertical wind shear) might alter the amount of entrainment they experience.

In the current study, idealized, 3D, high-resolution numerical simulations of supercell thunderstorms are used to evaluate entrainment and its effects during the developing and rotating stages of the storms. Entrainment is quantified using an algorithm that first estimates the sub-grid scale edge of the 3D cloud core, defined with specific condensate and vertical velocity thresholds, and then calculates the mass flux into that core. As entrainment proceeds in time, the resulting dilution of the core condensate is tracked. Multiple realizations in the same storm environment are created by altering the storm forcing type (heat flux versus “warm bubble”), the horizontal area over which the forcing is applied, and the vertical wind shear.

Results show that vertical wind shear can greatly enhance the entrainment rate into the developing storms, being nearly twice as much locally but even exceeding hundreds of percent more when integrated over the entire storm in time. Similar to past studies, the proportionality of entrainment and dilution in the developing stages of the storms depends upon the local properties
of the entrained air and the occurrence of multiple thermals. The method of initiating simulated storms with a “warm bubble” was also found to be detrimental to representing the turbulent eddies required for accurate simulations of entrainment, in the developing stages. Surprisingly, entrainment in the rotating stages of the storms decreased slightly but not substantially, counter to theoretical predictions.
ACKNOWLEDGEMENTS

Funding for this research was provided by National Science Foundation grants AGS – 1502398 and AGS – 1725190 under Sonia Lasher-Trapp. Thank you to George Bryan for the creation and matinence of CM1. All simulations and calculations were performed on the Blue Waters sustained-petascale computer, amintained by the National Center for Supercomputing Applications, supported by the National Science Foundation (awards OCI-0725070 and ACI-1238993) and the State of Illinois.

A very special thank you to my advisor Professor Sonia Lasher-Trapp. I cannot express how thankful I am for all that you have taught me as a professor, advisor, and person. It was a privldege to work with you as your support and assistance was never-failing. I thank all faculty and staff at the University of Illinois, for an incessant eagerness to help one another is what makes the Department of Atmospheric Sciences so great.

Thank you to Adrienne King. Your continuous support and encouragement was more helpful than you will ever know. Words can’t explain how truly amazing you are.

And finally, a special acknowledgment to my parents for all of their hard work and extra effort to help me succeed. For all that you have taught me and your unconditional love, I will always be grateful.
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CHAPTER 1: INTRODUCTION

1.1 Entrainment and dilution in weak wind shear environments

*Entrainment*, the process by which turbulent clouds mix in environmental air via overturning eddies at the cloud edge, has large implications on the amount of precipitation they can produce (e.g. Jonas and Mason 1982, 1983, Blyth 1993, Cooper et al. 2013), as well as their strength and longevity (Derbyshire et al. 2004, Del Genio 2012). Entrainment of dry, cool, environmental air decreases the water content that can be converted to precipitation and reduces the buoyancy through latent and sensible cooling. These effects of entrainment may be referred to as *dilution* of the cloud core.

In the past, entrainment and dilution have been studied in the laboratory (Scorer and Ronne 1956, Scorer 1957, Woodward 1959), with aircraft observations (e.g. Warner 1970, Blyth et al. 1988, Blyth et al. 2005), and using numerical models (e.g. Carpenter et al. 1998; Blyth et al. 2005; Dawe and Austin 2011; Yeo and Romps 2013; Moser and Lasher-Trapp 2017, 2018). It has been documented that the transient nature of clouds is due to multiple thermals within an updraft (Blyth and Latham 1993; Carpenter et al. 1998; Damiani et al. 2006), where a *thermal* is defined as an intermittent, buoyant fluid element with a corresponding toroidal circulation (Fig. 1). Studies have shown that growing cumulus clouds entrain air as a result of the overturning toroidal circulation associated with each thermal (e.g. Woodward 1959; Blyth et al. 2005). Stronger updrafts within the toroidal circulation are thought to cause larger entrainment rates (Keuthe 1935; Morton et al. 1956; Woodward 1959; Turner 1964).
Older studies equated entrainment rates and dilution rates, but more recent studies have shown how the dilution rate can be modified when the characteristics of the entrained air have been altered compared to those of the environment. When the entrained air was detrained earlier from a given thermal and reingested (Yeo and Romps 2013), or modified by the passage of a previous thermal, dilution decreases relative to that assumed from the entrainment of undisturbed environmental air (French et al. 1999, Moser and Lasher-Trapp 2017). This disproportionality has been discussed in other studies that also compared entrainment and dilution (Dawe and Austin 2011, Kirshbaum 2011). Yeo and Romps (2013) calculated that over half of all entrained parcel trajectories in their simulated cloud were previously detrained from it, decreasing its rate of dilution. Moser and Lasher-Trapp (2017) showed that for successive thermals, new thermals dilute less when rising through the remnants of the previous thermal. The entrainment of moist air and the resulting slower dilution can maintain the buoyancy of the cloud longer, allowing clouds to reach higher cloud top heights, and preserve more of the liquid water inside the cloud, increasing the amount of precipitation produced.

From the Small Cumulus Microphysics Study (SCMS), aircraft observations of cumulus clouds showed only a small percentage of cloudy regions (~20%) contained a liquid water content (LWC) 80% or more of the upper theoretical limit, the adiabatic liquid water content, and that these regions decreased in occurrence with altitude (Blyth 2005). However, very small values of LWC can exist inside a cloud (Blyth et al. 2005), as well as values essentially at the adiabatic limit near the updraft center (Musil et al. 1986; Heymsfield et al. 1978; Jensen et al. 1985; Raga et al. 1990, Blyth 2005). Smaller values can result from entrainment, and/or removal of water by precipitation. Larger values, even those exceeding the adiabatic limit, can result from limited or
no entrainment, and/or a secondary thermal rising through the remnants of a previous one (e.g. Roesner et al. 1990, Moser and Lasher-Trapp 2017).

1.2 Entrainment and dilution in strong wind shear environments

Very few studies considering entrainment and dilution in cumuli developing in environments with strong vertical wind shear are in the published literature. The classic observational study of Kitchen and Caughey (1981) provided the first source of information on entrainment in environments with vertical wind shear. Using a suite of vertically distributed instruments along a tethered balloon, they observed that the toroidal circulation near cloud top was asymmetrical, producing a flow pattern where the overturning is greater on the downshear side of the updraft, which they called a ‘P-type circulation’ (Fig. 2). This circulation is thought to be the primary driver of entrainment on the cloud scale, as the symmetrical toroidal circulation is for cumuli in non-sheared environments. Entrainment and dilution rates are often assumed to be greater in cumuli developing in environments with strong vertical wind shear (Malkus 1954, Scorer and Ludlam 1953, Blyth et al. 2005), but quantitative studies are lacking. Some earlier studies (Malkus 1952, Scorer and Ludlam 1953) discussed (but did not evaluate) the possible influence of the lean with altitude of a cumulus cloud growing in an environment with vertical wind shear, such that cloudy parcels must travel a longer distance (and thus require more time) to reach a particular height, allowing entrainment to act longer up to that height.

Strong vertical wind shear is a necessary ingredient for deep convection to organize and persist, by preventing rain and other hydrometeors falling into their updrafts (Ludlam 1963). An environment with strong vertical wind shear (Weisman and Klemp 1982; Weisman and Klemp 1984) and clockwise turning with increasing speed of the winds with altitude (Davies-Jones et al.
is conducive for long-lived thunderstorms called *supercells*. A supercell is distinguishable from other convection through the presence of a rotating updraft (Forbes 1981). The interaction between the storm updraft and environmental wind shear creates nonhydrostatic perturbation pressure gradients that are influential in strengthening updrafts (Weisman and Klemp 1984). It has been hypothesized that entrainment and dilution are much less for a rotating updraft in a supercell thunderstorm compared to a non-rotating updraft (Lilly 1986), but a quantitative analysis has not been performed. A better understanding of entrainment and dilution in the *developmental stage* (i.e., prior to any updraft rotation), and the *rotating stage*, is crucial for understanding and predicting the initiation, as well as the strength, longevity, and precipitation, of supercell thunderstorms.

### 1.3 Numerical methods for calculating entrainment

Because it is currently impossible to measure the influx of air into the entire perimeter of a real cloud or storm with any kind of accuracy, only calculations of the entrainment into numerically-simulated clouds and storms is practical. A review of the literature shows multiple methods have been used.

*The bulk-plume method* (Tiedtke 1989; Schumann and Moeng 1991; Siebesma and Cuijpers 1995; Siebesma 1996) calculates the convective flux of a conserved variable (a “tracer”) such as total water or liquid-water potential temperature, and tracks its depletion in time. Such calculations are an estimate of dilution rather than entrainment, however. This method is also of limited use because it assumes the clouds are horizontally homogenous and non-precipitating (so that the conserved variables are truly conserved).
Over the last 20 years with better computing power, methods of calculating entrainment have shifted to a more direct approach.

- Romps (2010) used passive particle tracers that move with the air in a numerically simulated cumulus cloud. The values of entrainment must be averaged over the time required for a grid cell to transition from the environment to the cloud core. While providing quantitative information about entrainment (an advantage over the bulk-plume method), this method has the disadvantage of the entrainment values being averaged over different time scales. Consequently, this method is not able to quantify instantaneous rates of entrainment.

- Dawe and Austin (2011) proposed a different direct method that calculates the flux of mass through a core surface (i.e., entrainment), where the core is defined by threshold values of vertical velocity and mass of condensate. To enhance accuracy, the core surface is identified on the sub-grid scale to decrease the dependency upon the model grid spacing using a tetrahedral interpolation scheme, which breaks down each grid box into 48 tetrahedrons. This method is advantageous for calculating entrainment instantaneously over a smaller spatial scale, but like the Romps (2010) method, the level of accuracy still depends on how well the entraining eddies are resolved by the model grid spacing. These direct methods require high temporal output in order to take into account the movement of the cloud core surface and accurately calculate entrainment.

Despite using different direct methods of calculating entrainment, the total entrainment calculated by both of these direct methods correlated well, when integrated over the length of simulations as long as the grid spacing resolves the clouds adequately (Romps 2010, Dawe and Austin 2011). Romps (2010) showed that the bulk-plume method underestimated entrainment by
a factor of two when compared to direct methods. Both Romps and Dawe and Austin attributed the underestimation in the bulk-plume method to the fact that it instead was calculating dilution, rather than entrainment. In some cases, dilution can proceed more slowly due to entrainment of the surrounding moist shell (e.g. Dawe and Austin 2011, Hannah 2017), entrainment of detrained cloudy air (Yeo and Romps 2013), and entrainment of previous thermal remnants (Moser and Lasher-Trapp 2017).

1.4 Research objectives

Deep cumulus clouds around the world are responsible for high rates of local precipitation. The high societal impacts and the low skill for quantitative precipitation forecasts (QPFs) of these events remains an important issue (Fritch and Carbone 2004, Barthold et al. 2015). Summertime QPF is especially difficult due to the prevalence of deep convection in strongly sheared environments; knowledge is lacking regarding the effects of entrainment and dilution upon its initiation, and the microphysical processes leading to its precipitation. The current study seeks to contribute new quantitative knowledge of entrainment into thunderstorms growing in an environment with strong vertical wind shear. Numerical simulations of developing supercell thunderstorms in a highly sheared environment are created at high resolution, and entrainment into the core of the storm is directly calculated as the cloud/storm evolves through its developing and rotational stages. Sensitivities of the calculations to the environmental winds and storm initiation methods are evaluated, and the effects upon dilution of water mass in the storm are quantified when possible.
1.5 Figures

**Figure 1:** Vertical cross section of the toroidal circulation (curved arrows) within a cumulus cloud growing in an environment without vertical wind shear. Vertical arrow indicates center of the cloud updraft.
Figure 2: As in Fig. 1, except in an environment with vertical wind shear, where arrows at left indicate relative wind direction ('x' denotes wind into the page) and relative wind speed.
CHAPTER 2: METHODS

2.1 Model description

The Cloud Model 1 (CM1) version 18.3 was used for this study. CM1 is a non-hydrostatic, 3D, idealized numerical model used for simulating mesoscale processes in the atmosphere, such as supercells (Bryan and Fritcsh 2002). The model integrates the governing equations to find all components of velocity, the non-dimensional pressure, water and ice mixing ratios, and potential temperature. Calculations are made on an Arakawa-C grid, which has the scalars located at the center of each grid box and the velocities located at the center of each grid box face. Advection of scalar quantities and momentum is calculated by integrating fifth-order spatial derivatives in time. The Coriolis force is included in these simulations. The base state (environment) of all simulations is in hydrostatic balance, time-invariant, and horizontally-homogeneous, with thermodynamic and wind characteristics given by the sounding of Weisman and Klemp (1982), with a quarter-circle hodograph (Figure 3).

There is 100 m grid spacing in all directions throughout the entire domain of 104 km x 104 km x 20 km. All scalar and vector quantities are output every 6 seconds, a short time interval needed for the entrainment calculations. To properly represent acoustic waves, a time-splitting technique (Klemp and Wilhelmson 1978) splits the 0.2 second time step into 10 smaller steps. Sub-grid scale turbulence is represented by a 1.5 order turbulence scheme (Deardorf 1980). Rayleigh damping is placed in the domain at 17 km height and above, to prevent wave reflection off of the top of the domain. The top and bottom boundary conditions are free-slip, and the east, west, north, and south boundary conditions are open (radiative). To represent the microphysical processes that
occur in deep convection, the NSSL microphysics scheme is used. This is a two-moment scheme predicting number concentration and mass for 6 separate classes: water vapor, rain, cloud water, ice, snow, graupel, and hail (Mansell et al. 2010). Density of graupel and hail are predicted in this scheme to allow improved representation of their fall velocities.

2.2 Initiation techniques

To perturb the hydrostatic base state, two different initiation techniques are used. As a sensitivity study, the traditional “warm bubble” approach (e.g. Klemp and Wilhelmson 1978) was used, but for all other simulations reported here, a Gaussian heat flux was used, as described below.

The warm bubble is an instantaneous, positive potential temperature perturbation inserted into the domain at the start of the model integration (Fig. 4a). The strength of the potential temperature perturbation was 1 K and centered at a height of 1500 m, collocated with the level of free convection (LFC) in order to initiate convection quickly. This warm bubble had dimensions of 1500 m in the vertical, and two different simulations varied the bubble diameter as 5 or 10 km, in order to investigate any dependency upon updraft width.

The preferred method of storm initiation in this study is the Gaussian surface heat flux used by Carpenter et al. (1998). The heat flux is a maximum at the surface and decreases exponentially radially and vertically, approaching zero at 1500 m altitude in the domain. This heat flux can be expressed mathematically according to the equation:

\[ H(t) = H_g(t) \times e^{-\left(\frac{x^2}{\sigma^2} + \frac{y^2}{\sigma^2}\right)} \times e^{-\left(\frac{z}{\alpha}\right)} \]

where \( H \) is the amplitude of the maximum heating, \( \sigma \) is the horizontal width, and \( \alpha \) is the height of the Gaussian. This heating starts at the beginning of the simulation and linearly increases for 5 minutes, until \( H \) reaches 500 W m\(^{-2}\). This heating is sustained for 24 minutes and then linearly
decreases for 1 minute, totaling 30 minutes of heating (Fig. 4b). Approximately 68 percent of the heating occurs within the value of $\sigma$. Two different simulations were run with $\sigma = 5$ or 10 km, again to test for any dependency of entrainment upon updraft width.

The Gaussian heat flux inserts more total energy into the system, but it is dispersed over a larger area and over a longer period of time compared to the warm bubble. The center of the warm bubble was located at the height of the level of free convection (LFC), so it was able to quickly initiate a deep convective cloud. In contrast, the Gaussian heat flux was located primarily at the surface, so it required almost 60 minutes to initiate the storm. Two simulations were run for each initiation technique, varying the width of the forcing, to test the laboratory-derived relationship of the inverse proportionality between radius of the cloud core and entrainment that is often used in entrainment parameterizations. The two different simulations produced storms that were comparable in size, however so this relationship was not able to be tested. Hannah (2017) simulated numerous cumulus clouds while varying the radius and found a weak negative relationship for dilution, but not entrainment. For a cloud with a larger radius there was more protection around the core of the cloud, resulting in less dilution and a negative relationship.

2.3 Direct calculation of entrainment

To calculate entrainment in this study, the direct method based on the work of Dawe and Austin (2011) was used. This algorithm measures the mass flux through a cloud core defined by preset thresholds for condensate mass, and vertical velocity. This direct method of calculating the mass flux emulates the calculation of the amount of environmental air being entrained or detrained into/out of the core surface. For this study, entrainment is calculated between six-second model output, to capture the rapidly changing core surface. Each grid box is sub-divided into 48
tetrahedrons in order to better resolve the cloud core surface, and to better predict the amount of mass moving in and out of the surface. Entrainment can be represented mathematically by:

\[
e - d = \int_C \rho (u_i - u) \cdot dC
\]  

(2.1)

where the left-hand side consists of local entrainment \( e \) and detrainment \( d \) rates respectively, and the right-hand side is the mass flux of air moving into and out of the core surface \( C \), where \( \rho \) is the air density (units of kg m\(^{-3}\)), \( u_i \) is the velocity vector of the surface (positive for directed outward, in units of m s\(^{-1}\)), \( u \) is the velocity vector of the air (units of m s\(^{-1}\)), and \( \hat{C} \) is the vector normal and inward to the core surface (units of m\(^2\)). For example, when the magnitude of the velocity of the core surface \( (u_i) \) is greater than that of the air \( (u) \), the mass flux occurs inward towards the center of the core and net entrainment occurs. On the other hand, when the velocity vector of the core surface \( (u_i) \) is less than the velocity vector of the air \( (u) \) the mass flux is outward towards the environmental air, net detrainment occurs. Although density and velocity are predicted by the model, \( u_i \) and \( C \) are not. To compensate for the specific structure of the Arakawa-C grid, Dawe and Austin (2011) show that the time derivative of cloud core mass can be decomposed using the Leibnitz integral:

\[
\frac{d}{dt} \int_{V(t)} \rho \, dV = \int_{V(t)} \frac{d\rho}{dt} \, dV + \int_{C(t)} \rho u_i \cdot dC + \int_{W(t)} \rho u_i \cdot dW
\]  

(2.2)

where \( V \) is the core volume (units of m\(^3\)) and \( W \) is the vector normal and inward to the grid wall surface and has a magnitude equal to the grid wall area occupied by the cloud core volume (units
of \( m \)). Assuming that the density change for one time step \((d\rho/dt)\) is very small and \( u_i \) is zero at the grid cell wall due to the grid wall being stationary, Eq. (2.2) reduces to

\[
\rho \frac{d}{dt} \int_{v(t)} dV = \int_{c(t)} \rho u_i \cdot dC
\]  

(2.3)

Eq. (2.3) can then be substituted into Eq. (2.1) to give

\[
e - d = \rho \frac{d}{dt} \int_{v(t)} dV - \int_{c} \rho u \cdot dC
\]  

(2.4)

Applying the divergence theorem to simplify the flux integral through the core surface:

\[
\int_{w} \nabla \cdot (\rho u) \ dV = \int_{c} \rho \ u \cdot dC + \int_{w} \rho \ u \cdot dW
\]  

(2.5)

By conservation of mass \( \nabla \cdot (\rho u) = 0 \), the two terms on the RHS of Eq. (2.5) are related by

\[
\int_{c} \rho \ u \cdot dC = - \int_{w} \rho \ u \cdot dW
\]  

(2.6)

Plugging Eq. (2.6) into (2.4) results in

\[
e - d = \rho \frac{dV}{dt} + \int_{w} \rho \ u \cdot dW
\]  

(2.7)

where the LHS again contains the local entrainment and detrainment rates, and the RHS is the mass flux of air moving into and out of the core surface. The first term on the right-hand side represents the changes in the core volume. For an expanding core, the velocity of the core surface is greater than the velocity of the air, and just as in Eq. (1.1), the mass flux will be directed inward and entrainment will occur. The second term represents the mass flux through the cloud core walls.
These two terms will offset each other so that simple advection of the core will not result in calculated entrainment.

For initial calculations of entrainment performed in this study, the perturbation winds (i.e., deviation of the winds from their environmental values) were inadvertently used. Later calculations were performed (or re-evaluated) with the total winds, i.e., perturbation plus environment components combined, and are those presented in the results section. Such later values of entrainment were found to be approximately 10% less than those calculated from the perturbation winds.

2.4 Calculation of dilution

As defined in Section 1.1, the *adiabatic liquid water content* (ALWC) is the theoretical upper limit for how much condensate can be produced by adiabatic cooling of a saturated parcel as it ascends to a given height above the cloud base. It can be quantified using the equation:

\[
ALWC(z) = \sum_{i=CB}^{z} (w_{s,i} - w_{s,i+1})
\]

(2.8)

where the ALWC (here expressed in g kg\(^{-1}\)) is the cumulative sum of the saturation mixing ratio (\(w\)) difference between two levels, integrated from the cloud base (\(CB\)) up to a given height (\(z\)). This value is useful to quantify dilution with respect to an adiabatic parcel, and here can be used to gauge the effects of entrainment, in the absence of precipitation.
2.5 Calculation of updraft helicity

During the analysis of the rotational stages of the storms, it was necessary to calculate the maximum updraft helicity to quantify the variability in the amount of rotation of the storm updrafts. Updraft helicity is defined as

\[ UH = \int_{z=2}^{z=5 \text{ km}} w \zeta \, dz \]  

(2.9)

where \( w \) is the vertical velocity (m s\(^{-1}\)) and \( \zeta \) is vertical vorticity (s\(^{-1}\)).

Using the values of this vertically-integrated quantity between 2 and 5 km altitude, for each column that is output by the CM1 model, the maximum at each time was used to quantify the amount of rotation within the storm updraft. At such a fine grid spacing (100 m), the UH calculated in this way, however, will be subject to small-scale variations within the updraft (of either vertical velocity or vertical vorticity), and less representative of the circulation around the edge of the updraft.
2.6 Figures

Figure 3: The environmental sounding used for all simulations in this study.
Figure 4: A vertical cross section of bubble initiation (a) and Gaussian flux after all heating has occurred (b). The radius of forcing is approximately 10 km in both cases.
CHAPTER 3: RESULTS

3.1 General behavior of the high wind shear simulations

Four simulations were run using the high-shear quarter-circle hodograph shown in Fig. 3. The storms in two simulations were initiated with the warm bubble approach, and the storms in the other two simulations were initiated with the Gaussian heat flux. Both techniques are described in Section 2.2. Differences in the behavior of the simulated storms, and their associated entrainment, were anticipated due to having different widths of the forcing, but did not produce any strong relationships. Differences in entrainment due to the different initiation methods and are now discussed.

3.1.1 Warm bubble cases

The warm bubble was used to initiate convection for two different simulations in order to provide two different realizations of a storm in a sheared environment (Table 1). One simulation, which will be referred to as FullBub, used a 10 km warm bubble, whereas a second simulation used a 5 km warm bubble and will be referred to as HalfBub. The HalfBub storm had a much stronger updraft during the early stages compared to the FullBub simulation (Fig. 5), and reached higher cloud top heights initially (Fig 6), likely due to the narrower updraft encountering less of a dynamic pressure gradient force near cloud top. For the FullBub storm, there was a higher buoyancy pressure at the top of the cloud and low buoyancy pressure at the bottom, which resulted in a stronger downward pointing vertical buoyancy pressure gradient force that impeded the acceleration from buoyancy. The narrower HalfBub storm was able to rise higher compared to the
FullBub because there was a weaker vertical pressure gradient acting through the depth of the cloud. After 22 minutes the maximum vertical velocities were comparable, and after 27 minutes the cloud top height was comparable between simulations.

For analysis of the developing stages of the simulated storms, horizontal cross sections of the vertical velocity and perturbation wind field at 5 km altitude were examined at every minute (Fig. 7). The end of the developing stage was determined by the time at which the wind field began to depict rotation, at 21 and 23 min for the HalfBub and FullBub cases, respectively (Table 1). Limiting the analysis to these time periods provides the opportunity to evaluate entrainment before updraft rotation can significantly influence the flow surrounding the cloud, and perhaps entrainment as well. The rotating stages of these storms were not studied further.

3.1.2 Gaussian heat flux cases

Two more simulations were created using the same environment but were initiated differently using the Gaussian heat flux. When using this initiation technique, the storms begin much later compared to the warm bubble initiation, for two reasons: (1) Despite more total energy added to the system using the Gaussian heat flux, it is added more slowly, over a period of 30 min rather than instantaneously as in the bubble initiation; and (2) because the maximum heating occurs at the surface, rather than at the center of the bubble at 1.5 km altitude, it requires more time to reach the level of free convection (LFC) and initiate convection. The wider storm (referred to as GausFull) develops a little more slowly (Figs. 5 and 6) compared to the narrower storm (referred to GausHalf), but does not differ as much as the cases initiated with a warm bubble. The developing stages were diagnosed using the same method (examining horizontal cross-sections of the vertical velocity and perturbation wind field at 5 km altitude) as for the warm bubble simulations. Because
of the slower development in these simulations, they needed to be run longer, to 130 min, to include the rotating stages. The beginning of the rotating stages was set to the time when there were two completely separated rotating updrafts (Fig. 8); the time during the initial storm split was not analyzed. Both simulations were analyzed beginning at 100 minutes and analyzed for the next 30 minutes (Table 1).

3.2 General behavior of the no wind shear simulation

One other simulation (referred to as GausHalfNOSHEAR) was created using the same thermodynamic conditions as the previous simulations but with no environmental winds throughout the depth of the domain, and using the Gaussian heat flux initiation. When vertical wind shear in the environmental wind field is absent, the storm initiates 7 minutes earlier, and the maximum updraft speed and cloud top height increase more quickly (Figs. 5 and 6). However, without the presence of environmental wind shear, the storm develops, its maximum updrafts persists for 25 minutes, but then the rain it produces falls back into its updraft, and the storm dissipates. The developing stage of this storm is analyzed from its inception until it reaches its peak updraft speed at 50 minutes (Table 1). In the absence of environmental vertical wind shear, no rotation develops in the storm.

3.3 Entrainment during the developing stage: no wind shear vs strong wind shear

To gauge the effects of strong vertical wind shear on entrainment and dilution, a strong wind shear case (GausHalf) and another with no background wind (GAUSHalfNOSHEAR) were compared. All other aspects of the simulation setup were identical for the two cases.
Entrainment was calculated at every grid point situated at the core edge (defined as total cloud and ice mixing ratio greater than 0.1 g/kg and vertical velocity greater than 1 m/s), averaged horizontally and normalized by the core surface area over a grid box depth, and output as a function of height for each time. This instantaneous vertical profile of entrainment represents the rate of mass being mixed inward through the cloud core surface at each vertical level and is normalized by the surface area at each level to make fair comparisons among cores that are potentially of different sizes between different simulations. Entrainment for the developing storm in the sheared environment at upper levels is as much as twice that in the no-wind environment, due to the formation of the P circulation (Fig. 9). By integrating the entrainment rate in time, the total mass entrained into the core can be calculated and compared for the time required for the clouds to reach the same cloud type height, or for the same period of time. When integrated over the time required for both storms to attain the same cloud top height of 8.6 km (Fig. 10), the calculations show that 334% more mass is entrained into the core for the storm simulated in an environment with strong vertical wind shear. Although dilution was not calculated for the no-shear case, the faster increase of its maximum updraft speed in time, compared to the strong wind shear case (Fig. 5) is indicative of the effects of this reduced entrainment upon the buoyancy contained within the storm core. If the integration of the entrainment over the storm core is instead conducted for the same amount of time rather than the time to reach a particular cloud top height), the storm simulated in the sheared environment entrains 86% more mass into the core over the first 76 minutes of its lifetime (Fig. 11). Thus, however it is analyzed, the storm simulated in a sheared environment entrains much more mass than that in a non-sheared environment. Because the entrainment calculations were normalized by either the core surface area or the core volume, the greater values in the sheared
cases cannot be attributed to greater storm core surface areas in the tilted updrafts (Markowski and Richardson, 2010).

3.4 Entrainment during the developing stage: weak wind shear vs strong wind shear

Clouds in the developing stages from the GausHalf and GausFull simulations were also compared to those simulated by Moser and Lasher-Trapp (2017), which used an observed sounding from the Convective Precipitation Experiment (COPE) and were conducted in an environment with some, but not strong, vertical wind shear. The analysis was performed for similar cloud top heights and maximum vertical velocities, and the values were again normalized by the respective core surface areas. Throughout the entire depth of the clouds, the entrainment was three to five times greater for the stronger shear cases (Fig. 12).

3.5 Entrainment and its effects on dilution in the developing stage with strong wind shear

Although dilution is a result of entrainment, past studies have shown that this relationship can be modified by the changing thermodynamic properties of the air that is entrained. Here, the relationship between entrainment and dilution are examined for developing storms growing in strong vertical wind shear. In both GausHalf and GausFull simulations, the entrainment rate was increasing during the entire developing stages (Fig. 13). In contrast, the rate of dilution (Fig. 14) fluctuated in time during this period. The dilution rate can be roughly diagnosed by the ratio of the maximum total water mixing ratio to the ALWC at that height.

These fluctuations in dilution can be separated into four different periods. The first section (from cloud initiation until a cloud top height of approximately 2.5 km) had evidence of undiluted parcels, where the maximum total water mixing ratio followed the adiabatic liquid water content.
(gold curve in Fig. 7). The second section, from a cloud top of 2.5 km to 4.25 km, started to demonstrate significant dilution (diverging from the ALWC at those altitudes). The third section, from cloud top heights of approximately 4.25 km to 6 km, still had evidence of the prior dilution, but the rate of dilution was less compared to the prior section, and paralleled the increase in the ALWC. The fourth section, from cloud tops of 6 km to 8 km, experienced significant dilution for the GausHalf simulation, whereas the GausFull simulation exhibited little or no dilution. An investigation of these different dilution rates is now presented.

### 3.5.1 Undiluted Section 1

From the genesis of the simulated clouds up until cloud top heights of 2.5 to 3 km, the maximum total water mixing ratio ranged from 80 to 90% of the ALWC value. Despite some entrainment occurring during this time, it had not diluted the entire core yet, as it is not an instantaneous process. Turbulent eddies first dilute the cloud core edge and proceed inward with time.

### 3.5.2 Major Dilution Section 2

Once cloud tops began rising above 2.5 to 3.0 km, the maximum total water mixing ratio started diverging from the ALWC until the clouds reached an altitude of 4.25 km. The entrainment rate was still increasing during this time (Fig. 13) due to the cloud reaching higher altitudes where stronger wind shear enhanced the overturning of the downshear entraining eddy. These stronger entraining eddies had time to penetrate into the cloud core, causing an enhancement in dilution. Vertical cross sections at the end of Section 1 (Fig. 15a) and the start of Section 2 (Fig. 15b) show the perturbation wind vectors perpendicular to the cloud core surface on the downshear side.
becoming stronger, enhancing the dilution during this time and eroding the maximum total water mixing ratio to be only 63% of the ALWC at 55 minutes when the cloud top was 3.4 km.

3.5.3 Some Recovery from Dilution in Section 3

At a cloud top height of 4.0 km in the previous stage of major dilution, the maximum total water mixing ratio was tracked within the first ascending thermal of this period (Fig. 16). Above a cloud top height of 4.25 km, the first thermal still continued to experience significant dilution of the maximum total water mixing ratio due to entrainment as it rose into pristine environmental air. However, a second ascending thermal at this time contained the maximum total water mixing ratio as it rose partially through the wake of the first (Fig. 17). The maximum total water mixing ratio, now associated with the second thermal, no longer diverged from the ALWC curve at this time (Fig. 14). As this second thermal rose through the remnants of the first thermal and entrained moist and possibly even buoyant air, dilution slowed, increasing the percentage of the ALWC to 86%. The entrainment of more buoyant and moist air allowed the later thermals to rise to higher altitudes. This behavior was seen up until a cloud top height of 6.0 km.

3.5.4 Major Dilution Section 4

At a cloud top height of 6.0 km, the HALFGAUS simulation had significant dilution occurring until the cloud reached a height of 8.0 km. The cause for the significant dilution was due to both entrainment of environmental air, as well as precipitation falling out of the core (Fig. 14, dashed red line). Vertical composites of the total water mixing ratio (Fig. 18) show that at a cloud top height of 5.6 km (Fig. 18a), before the major dilution, there is a maximum total water mixing ratio exceeding 7 g kg\(^{-1}\). This maximum rose through the remnants of the previous thermals and
did not experience much dilution. One minute later (Fig. 18b), this maximum had distinct notches on each side but moreso on the downshear side, indicative of the P-circulation beginning to entrain environmental air and eroding the core edges. Yet another minute later (Fig. 18c) the entrainment of environmental air was able to penetrate the core and erode the maximum in total water mixing ratio. At this time the maximum total water mixing ratio was reduced to 62% of the ALWC. The corresponding divergence from the ALWC shown in the time series of dilution (Fig. 14) occurred until a cloud top height of approximately 7.0 km. Part of this major dilution also resulted from precipitation falling out of the core (Fig. 14).

3.6 Entrainment in the rotating stage

It is often assumed, based on theoretical predictions by Lilly (1986), that “helical flow” (i.e. a rotating updraft) is less susceptible to turbulent diffusion and dissipation (and thus entrainment). However, the extrapolation of this hypothesis to a reduction of entrainment within rotating updrafts has not been tested directly. Using two different realizations of a supercell thunderstorm (GausHalf and GausFull), this hypothesis is tested by computing the entrainment during the developing and rotating stages. For the calculation of entrainment during the rotating stages, the storm core has been defined as having water and ice mixing ratio greater than 0.1 g/kg and vertical velocity greater than 1 m/s, the same values as used to define the core during the developing stages. Thus, the values of entrainment calculated during the different storm stages can be compared. Figure 19 shows that during the developing stages, as the storm was strengthening and deepening, the entrainment rate was increasing in both simulations. As the storms transitioned to the rotating stages, however, there was a small decrease in the entrainment rate, but it was still substantially strong compared to the developing stage. This magnitude of
entrainment rate maintained itself until the end of the analysis period, with no sign of further
decrease. Thus, the common assumption that rotating updrafts entrain minimally does not appear
to hold in these simulations. However, some uncertainty in these results exists, particularly in
assessing if the definition of the core during the rotating stages truly represents entrainment into
the main core of the storm, or if it has broken into many fragments.

The hypothesized relationship between rotation and entrainment was further evaluated
using the correlation between the vertically-integrated entrainment rate at each time and the
maximum updraft helicity (UH), an indication of the magnitude of the rotation of the updraft, as
described in Section 2.5. The calculations show that there was a slight negative correlation
between entrainment and UH for the GausHalf case (Fig. 20). This would seem to somewhat
support the argument that updraft rotation decreases entrainment into the updraft, although the
entrainment rates were still high compared to the developing stages. However, in contrast, the
GausFull simulation shows no such correlation, since it lacked much variability in both UH and
entrainment over this time period. It is uncertain at this time why the two simulations behaved
differently in this regard; further investigation of the storm dynamics, or a different quantification
of storm updraft rotation, may explain these different results.

3.7 Entrainment for different initiation techniques

The warm bubble initiation method is commonly used for idealized thunderstorm
simulations due to its ability to produce a storm quickly (as shown in Fig. 5 and 6), making it
computationally efficient. Despite the computational advantages, this unrealistic warm
perturbation, introduced into the model domain instantaneously, has some dynamical
disadvantages. It produces a single rapidly growing thermal with very little turbulence near cloud
edges in the early stages. This limits the total amount of entrainment (Fig. 21) and likely dilution as well, allowing the storm to intensify rapidly and quickly produce precipitation. On the contrary, the Gaussian heat flux initiation has a closer analog to nature. This method produces multiple, separate thermals rising upstream of their predecessors on a much slower time scale, allowing for a larger spectrum of turbulent eddies to form (Fig. 22). These turbulent eddies near cloud top are the mechanism by which entrainment (and dilution) occur (Fig. 23), resulting in slower storm development and a delayed onset of precipitation, compared to the warm bubble initiation.

### 3.8 Table and Figures

<table>
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<th>Simulation Name</th>
<th>Forcing Type</th>
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<th>Developing Stages Height</th>
<th>Rotating Stages Time of Analysis</th>
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**Table 1:** Names and analysis details of simulations used in study.
Figure 5: Time series of the maximum vertical velocity for each of the 5 simulations used in this study, as noted in the legend.
**Figure 6:** As in Fig. 5, except for maximum cloud top height.
**Figure 7**: Example of horizontal cross section of vertical velocity (values in m s$^{-1}$ given by color scale) and overlaid total wind vectors (scale at bottom right) near 5 km altitude, used to diagnose the end of the developing stage for the GausHalf simulation.
Figure 8: As in Fig. 7, except here diagnosing the beginning of the rotating stage for the GausHalf simulation.
Figure 9: Comparison of the horizontally averaged, instantaneous, vertical profiles of entrainment at 4 different times during the developing stages, for the storm environment with no wind shear (blue), and with strong vertical wind shear (red). The respective times for the profiles are listed in the respective keys for the respective simulation.
Figure 10: Comparison of the total mass entrained (normalized by the core volume) in an environment with weak wind shear (magenta), and in an environment with strong vertical wind shear (red), integrated from storm initiation until each reached a storm top height of 8.6 km.

334% more mass entrained in sheared environment for same cloud top height.
**Figure 11:** As in Fig. 10, except entrainment integrated for the same length of time (76 minutes) for both simulations.
**Figure 12:** Comparison between the horizontally averaged, instantaneous, vertical profiles of entrainment (top row) averaged over 5 different clouds (and for 5 different simulations given in legend) developing in an environment with weak wind shear from Moser and Lasher-Trapp (2017), and (bottom row) averaged over a single cloud growing in an environment with strong vertical wind shear, for two different simulations.
Figure 13: Vertically-integrated values of entrainment versus cloud top height during the developmental stage of each simulation as noted in the legend. Black numbers along curves represent time in minutes for each simulation.
Figure 14: Maximum total water mixing ratio within the core for each simulation (solid red and blue lines) versus cloud top height, and the adiabatic liquid water content (gold line) used for calculating dilution. The maximum precipitation mixing ratio (summed rain, graupel, hail, and snow) outside of the core (dashed red and blue lines) illustrates losses due to precipitation rather than entrainment.
Figure 15: Vertical cross sections through the maximum total water mixing ratio for the GausHalf simulation, with perturbation velocities overlaid. Black outline represents the cross-sectional area of the core surface. Panels (a) and (b) are during the first period having minimal dilution, while panels (c) and (d) are during the second period where significant dilution was occurring.
**Figure 16:** Top: Vertical composite of cloud water mixing ratio in g/kg, and bottom: vertical cross-section of cloud water mixing ratio with perturbation wind vectors and core boundary (magenta curve) overlaid. First thermal discussed in text is near the cloud top.
Figure 17: As in Fig. 16, except showing the second thermal (maximum in cloud water shown in both panels near vertical grid point of 30) rising through the wake of the first thermal during the third section of dilution, as discussed in the text.
Figure 18: Vertical composites of total water mixing ratio (g/kg) for the HALFGAUS simulation.
Figure 19: Time series of the core volume-normalized, vertically-integrated entrainment rate during both development and rotating stages.

Figure 20: Entrainment versus maximum updraft helicity during the rotating stages of the simulations, as discussed in text. Correlation computed from the red line fit to the GausHalf case as labeled.
**Figure 21:** Total amount of entrained mass normalized by the cloud surface volume during the development stage for all the simulations conducted with vertical wind shear.
Figure 22: Vertical cross sections of total mass mixing ratio, with perturbation wind vectors overlaid, for the BubHalf (a) and GausHalf cases (b).
Figure 23: Comparison of the horizontally averaged, instantaneous, vertical profiles of entrainment for 2 warm bubble simulations and 2 Gaussian cases for the same cloud top height. Stronger entrainment near cloud top is circled in brown. The respective times of the profiles are listed in the legend.
CHAPTER 4: CONCLUSIONS

4.1 Summary and main findings

Five numerical simulations of storms produced in thermodynamically identical environments, but with different degrees of vertical wind shear, or different storm initiation methods, have been used to study some fundamental aspects of the entrainment into storms. Entrainment was calculated directly into the surfaces of cores defined with particular mass and updraft speed thresholds, and normalized by the core surface areas or volumes to compare among different simulations. The analysis was divided into different stages of the storm evolution, consisting of the “developing stage”, i.e., while the maximum storm top heights were still ascending, and the “rotation stage”, during which time the storms had already split into two distinct counter-rotating updrafts.

Directly calculating entrainment into the cores of developing storms growing in environments with strong vertical wind shear versus no wind showed that for similar cloud top heights, the entrainment rate was as much as 2 times greater in areas associated with the P-circulation near the ascending storm tops in the cases with strong wind shear. The stronger circulation on the downshear side is responsible for entraining over 300% more mass when integrated over the time required to reach the same storm top height. By simply comparing the entrainment over the same 76 minutes of both developing storms, over 80% more mass was entrained into the storms growing in a sheared environment. When results are compared to simulations conducted in environments that are also thermodynamically different, even greater differences in entrainment may occur.

Similar to past studies, the evaluation of entrainment and dilution in the developing stages of the storms showed that entrainment causes dilution, but their proportionality depends upon the
local properties of the entrained air. In the developing stages, multiple thermals were observed rising one after another, when the simulations were initialized with a surface heat flux. The first thermal experienced a brief period of undiluted ascent while entraining pure environmental air, as time is required for the entraining eddies to penetrate inwards and dilute the maximum total water mixing ratio. As the cloud core reached higher heights and stronger wind shear, the entraining eddies were enhanced on the downshear side and were able to further penetrate the core and enhance dilution. As the first thermal diluted, a second thermal experienced nearly undiluted ascent as it rose partially in the wake of the first, but as it ascended to greater heights it began to entrain pure environmental air, rapidly diluting the maximum total water mixing ratio.

In the rotating stages of the storms simulated in an environment with strong vertical wind shear the entrainment rate decreased slightly but not substantially. The hypothesis that helical flow is less susceptible to entrainment was tested by comparing the entrainment rate to the rotation in the storm as quantified by the updraft helicity. While there was a small negative correlation for one of the simulations that supported this hypothesis, the other simulation was inconclusive, and thus this hypothesis warrants further study.

In the past, numerous studies have used the warm bubble to initiate convection. This method, albeit computationally efficient, is unrealistic in the sense that it produces a single rapidly growing thermal with very little turbulence near cloud edges in the early stages. The forcing is on such a large scale that it is not conducive for representing the larger spectrum of eddies responsible for entraining, and thus the overall entrainment was reduced compared to those storms initiated with a surface Gaussian heat flux. Thus, the bubble method is not recommended for realistic realizations of thunderstorm development.
4.2 Limitations

A general limitation of this study is that the supercell thunderstorms were simulated within an idealized thermodynamic sounding. This sounding is significantly more humid than those commonly observed, and may cause an underestimate of the diluting effects of entrainment. A large set of simulations, conducted with different thermodynamic and wind profiles, would help to test the generality of the results presented here.

Another limitation of this study is the method used for calculating dilution. Here, the amount of dilution was gauged by comparing the maximum total water mass to that from an adiabatic parcel, i.e., the ALWC. Once the storm heights exceed the level of the 0 °C isotherm, it is unclear how the ALWC should be calculated (i.e., to include ice), and precipitation fallout also violates this adiabatic assumption.

The result that entrainment is not greatly reduced once the storm updrafts rotate warrants further study, to ensure the analysis methods used here have not biased the results. Two specific aspects of this study especially require additional scrutiny: (i) the definition of the storm core into which entrainment is calculated; and (ii) the calculation of updraft helicity at individual grid points as a gauge of updraft rotation. While it was useful to retain the same definition of the storm core for comparison between the developing and rotation stages, a 1 m/s updraft core could encompass an area broken into many fragments in the later stages of the storm, which would bias theentrainment calculations. And although it was of great advantage to run the simulations for this study at a very high 100 m grid spacing to capture more entraining eddies, the storm updraft helicity calculated at each grid point is subject to small-scale variations within the updraft (of either vertical velocity or vertical vorticity), and thus less representative of the broader-scale updraft
circulation. An improved method to calculate this circulation might show a greater correlation with the entrainment at the rotation stages of the storms.

4.3 Future work

4.3.1 Dry layers

Future work should include the simulation of storms in different environments. The Weisman and Klemp (1984) sounding is significantly more moist than those often observed. Other simulations created in the same environment, but with dry layers of different magnitudes inserted at different heights, for example, may increase the amount of entrainment and dilution due to a larger buoyancy gradient along the cloud surface. Recommendations for the characteristics of these dry layers include their insertion at two different heights: 1.5-2.5 km and 3-4 km, and decreasing the water vapor mixing ratio within those layers linearly by 50% and then smoothed 500 m above and below. A possible sounding that could be used to initialize the future simulations is depicted in Fig. 24.

4.3.2 Precipitation efficiency

Deep cumulus clouds produce the majority of the earth’s precipitation but their strength, depth, and precipitation are controlled partly by entrainment and dilution. Better understanding of entrainment and dilution in the developing and rotating stages and how the rates fluctuate is important for microphysical processes that control precipitation formation. Tracking a Precipitation Efficiency (PE) would help relate entrainment/dilution to how much precipitation is being produced. One possible method for calculating PE would be a ratio of the cumulative sum of the total water mass being produced in the core to the cumulative sum of the water vapor mixing
ratio ingested into the base of the core. A second method would be a ratio of the condensate (cloud water and ice) to precipitation particles (rain, snow, graupel and hail) all within the core. Although each might have advantages/disadvantages, it is difficult to speculate at this time which method might be more productive.

4.3.3 Environmental entrainment

An additional aspect of the calculations that were not explored here were the differences in the entrainment rate computed from perturbation winds versus the “total” winds that include the environmental component of the winds as well. As shown in Fig. 25, calculations using the total winds showed a little less entrainment than for the perturbation winds. This difference may indicate a possible role of the environmental winds in “shielding” the cloud from entrainment somewhat, although additional study, including simulations in environments with different wind profiles, are needed.
4.4 Figures

**Figure 24:** Dry layer inserted into the sounding used in this study, from 1.5 km to 2.5 km, as discussed in the text.
**Figure 25:** Total entrainment over the cloud depth as a function of time, for two different simulations using the total wind (denoted “totz”) and the perturbation winds (denoted “pert”).
REFERENCES


