USING A VERTICAL INTEGRATION OF DOPPLER-DERIVED
DIVERGENCE TO ASSESS THUNDERSTORM
UPDRAFT/DOWNDRAFT CHARACTERISTICS

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The undersigned, appointed by the dean of the Graduate School, have examined the thesis entitled

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Abstract

Analyses of thunderstorm updraft and downdraft characteristics, such as magnitude and size, can reveal essential information pertaining to the strength of the thunderstorm itself. Such information can aid in assessing the threats that the storm of interest poses (or does not pose). Observing short-term trends in updraft and downdraft characteristics allows for better very-short-term forecasts (nowcasts) of thunderstorm intensity. Measuring vertical motion in the atmosphere is not easily attainable without expensive instrumentation. This project aimed to obtain thunderstorm updraft/downdraft magnitude using a vertical integration of Doppler-derived radial divergence (convergence) in accordance with the mass continuity equation. Three different cases representing three convective modes, ordinary, multicell, and supercell, were examined using this technique. The technique produced vertical velocity magnitudes that may not be accurate due to sources of error. Both the multicell and supercell case showed inconsistencies with the placement of the updrafts/downdrafts with respect to conceptual models of storm structure, but size and shape showed aligned well. Nevertheless, repeated magnitudes lead to the belief that there is precision in the results opening the door to operational feasibility.
Chapter 1 – Introduction

Thunderstorms bring with them many hazards. From lightning to flash-flooding, thunderstorms can pose a significant threat to life and property. The ability to predict certain hazards is essential for giving the public ample time to heed warnings and take action if necessary. The presence of these hazards within thunderstorms depends on the strength of the storm’s updraft. For example, for hail formation to occur a storm’s updraft must have a sufficient magnitude and width (Nelson, 1983; Zeigler et al., 1983). Updraft characteristics also indicate overall strength of the storm. Knowing the short-term trends in updraft strength can provide information for nowcasting storm morphology (e.g., strengthening updraft means increased probability for hazardous conditions).

Tracking hazardous thunderstorms as they occur has become an integral role for the operational and broadcast meteorological communities. Across the United States, 122 local National Weather Service (NWS) offices issue convective warnings with heavy reliance on a network of WSR-88D radars known as Next Generation Weather Radar (NEXRAD). Broadcast meteorologists facilitate “wall-to-wall” coverage, breaking into regular programming for dangerous storms. Using NEXRAD, meteorologists can provide near-real-time updates for the public. However, even Supplemental Adaptive Intra-Volume Low-Level Scan (SAILS) strategy only allows for 24 updates of the 0.5° scan per hour (NOAA Radar Operations Center). With only one update of the lowest scans every 2.5 minutes, storms are still faster than the instruments and meteorologists tracking
them. During this time, storms can rapidly intensify with seemingly no advanced warning. The extent to which meteorologists can produce very-short-term forecasts (nowcasts) of these storms is purely spatiotemporal; that is, they can use radar images and storm motion to estimate where and when a storm will be (Wang et al., 2017; Dixon and Wiener, 1993; Johnson, et al., 1998). Barring the use of complicated, computationally heavy, methods (Roberts et al., 2005; Ravuri et al., 2021), there is little meteorologists can do to nowcast storm intensity beyond using the pre-convective environment as a guide.

1.1 – Statement of Thesis

The goal of this study is to determine if forecasters can use a vertical integration of Doppler-derived radial divergence from a single Doppler radar to gain critical information on thunderstorm updraft and downdraft characteristics. The aim is for this information to provide a tool for meteorologists to, with relative ease, observe the morphology of a thunderstorm’s updraft and downdraft. Data from a WSR-88D representing different convective modes will be used to determine if the above method for calculating vertical wind speeds produces promising results. The objectives of this study are:

- Determine if a vertical integration of Doppler-derived divergence (convergence) can be used to accurately assess updraft and downdraft characteristics.
• Identify any temporal trends in updraft/downdraft magnitude and structure that the resultant vertical velocity field may display.

• Establish what, if any, applications this new method brings to thunderstorm nowcasting
Chapter 2 – Literature Review

To accomplish the objectives of this thesis outlined in section 1.1, background research into studies with similar goals was performed. Little research into using Doppler-derived divergence as a method of exploring thunderstorm updraft and downdraft characteristics exists, hence the focus of this study. Some previous studies have employed the use of Doppler radar to observe the 3-dimensional velocity field (e.g., Ray et al., 1975; Ray, 1976; Cifelli et al., 1996), but took different approaches. The literature review below will explore other topics related to nowcasting, vertical motion, and updraft characteristics. Section one will introduce a background into nowcasting, and current practices, with focus on their limitations. Section two will explore studies that have employed use of Doppler-derived divergence for other purposes.

2.1.1 – Nowcasting Background

The American Meteorological Society’s Glossary of Meteorology defines a nowcast as a “short-term weather forecast, generally for the next few hours,” (AMS Glossary, 2022). Nowcasts place heavy reliance on the availability of high spatial and temporal observations. These observations include, but are not limited to satellite, radar, lightning networks, surface observation stations, and radiosondes. The way that this data is distributed must be easily obtained and analyzed by a forecaster and understood well by the end users (Wang et al., 2017). The development of early nowcasting techniques occurred in the 1970s with the Chesapeake Bay Region Nowcasting Experiment (Browning, 1982). In his book, Browning (1982) identified five
main groups for which nowcasting is crucial: agriculture, construction, energy, transportation, and the general public/public safety. The scope of this thesis dealt with nowcasting in the context of public safety.

Browning (1982) identified characteristics that forecasters must establish to create an effective nowcasting system. These characteristics are variable or event, spatial domain, temporal domain, lead time, form of the forecasts, content and format of the information, and method of dissemination of the final product. Depending on the purpose for or the recipient of the nowcast, the thresholds to all of these characteristics will differ and thus, so will the specific nowcasting technique. Section 2.1.2 deals with a few of the many nowcasting practices oft used by forecasters in the context of thunderstorm updrafts.

2.1.2 – Nowcasting Practices

Since nowcasting’s infancy, subsequent work into developing methods has yielded a large toolkit of strategies ranging from complex computer software (Mueller et al., 2003) to mathematical approaches involving the vorticity equation (Sleigh and Collier, 2004). This section will offer an in-depth look into some of these techniques as they pertain to convective nowcasting. It is important to acknowledge that nowcasting can encompass other areas of meteorology such as winter weather, fire weather, etc.; however, this study purely focused on nowcasting of a convective nature.

Convective nowcasting, in the context of public safety, is primarily concerned with the accurate issuance of watches and warnings (e.g., severe, tornado, flash flood,
etc.). With this as the main objective, an accurate knowledge of the immediate location, motion, and intensity of the convection is crucial. The best way to achieve the high spatiotemporal resolution of data required to garner this information is through remote sensing (Wang et al., 2017). Many radar-based methods have been developed for thunderstorm and precipitation nowcasting (Roberts et al., 2006; Johnson et al., 1998; Dixon and Wiener, 1993). Additionally, techniques for assessing thunderstorm updrafts using remote sensing of lightning (Deierling and Petersen, 2008) can be applied to the field of nowcasting. Deierling and Petersen (2008) found that total lightning activity can be a good indicator of updraft volume, a useful characteristic when assessing storm strength (Nelson, 1983).

As mentioned in Chapter 1, traditional nowcasting techniques involving Doppler radar involved tracking storm cells through time and space. The work of Dixon and Wiener (1993) presented a simpler technique for cell identification and tracking compared to methods up to that point. They identified convective cells as ellipses using a reflectivity threshold of 35 dBZ, a volume threshold of 50 cubic kilometers to exclude ground clutter and noise, and subsequently calculated a storm’s aerial coverage by fitting an ellipse to this area. Once identified, the position of cell centroids was tracked from an initial time \( t_1 \) to the time of the next complete volume scan, \( t_2 \). Using this information, the algorithm calculated storm motion and created a short-term forecast through linearly extrapolating future centroid positions using this information. This nowcasting technique by Dixon and Wiener, called TITAN (Thunderstorm Identification, Tracking, Analysis, and Nowcasting), did not account for storm intensity by assuming
storm growth and decay follows a linear trend. Later developments of tracking algorithms improved upon the methods in TITAN (Johnson et al., 1998). The algorithm presented by Johnson et al. (1998), the Storm Cell Identification and Tracking Algorithm (SCIT) uses a slightly more complex approach. Instead of a singular reflectivity threshold of 35 dBZ, as was used by TITAN, SCIT uses a 7-threshold approach using 30, 35, 40, 45, 50, 55, and 50 dBZ. Additionally, SCIT also employs different spatial restrictions, requiring continuities along radials, across azimuths, and vertically across elevation angles. This method, now widely used by WSR-88Ds, performed significantly better than existing tracking algorithms. Nevertheless, this method still does not account for the nowcasting of convective intensity and evolution. SCIT will mishandle convective initiation and decay. Often, convective initiation occurs over an area where a previously existing storm resided in the last volume scan. This results in a miss of newly developing convection. Similar results occur with decaying convection as well. Additionally, post-event analysis can reveal areas where real-time, tracking algorithms break down in accuracy by using the subsequent position of cells to obtain better storm tracks (Lakshmanan et al., 2015). The common nowcasting methods outlined above are purely location-based, thus the need for more nowcasting techniques that consider convective morphology presents itself.

The previous nowcasting tools focused on merely tracking storm cells through time and space to extrapolate a future location at a given time. The work of Roberts et al. (2005) aimed to develop nowcasting tools for storm initiation/intensification. Using a fuzzy logic approach, they combined attributes from the Warning Decision Support
System (WDSS) severe weather detection algorithms and NCAR’s Auto Nowcast System (ANC). The ANC was presented in depth by Mueller et al. (2003). They used a number of parameters, of which, those involving convergence boundaries and vertical motion are of particular interest. Roberts et al. (2005) attained these parameters from the ANC, but similar characteristics may be derived using the divergence algorithm contained in WDSS-II and subsequently applied to the same fuzzy-logic, nowcasting approach. A common theme with nowcasting beyond traditional tracking algorithms is often the need for complex numerical models like the ANC. Ravuri et al. (2021) accurately predicted changes in rainfall rates over the United Kingdom using machine learning methods of generating future radar data. This high-computing machine learning technique was able to accurately predict increases and decreases in rainfall intensity as well as convective initiation and decay. Despite the heavy computing resources required, the machine learning method still struggled to produce accurate rainfall intensities beyond 2 hours in the future. Additionally, the study focused primarily on stratiform rain cases with little attention given to convective cases.

2.2 – Studies involving Doppler-derived divergence

The use of Doppler radar to obtain velocity derivatives is not a new concept. Browning and Wexler (1968) proposed a technique for measuring the kinematics of the wind field in widespread precipitation situations. Their technique involved a harmonic analysis of the velocity-azimuth display (VAD) of spatially uniform precipitation coverage. The study concluded that horizontal divergence was represented by the magnitude of the zeroth harmonic. Additionally, wind speed/direction and deformation
were represented by the amplitude and phase of the first and second harmonic, respectively. Perhaps the closest related study to this thesis, Cifelli et al. (1996) used modified versions of Browning and Wexler’s technique in consort with the continuity equation (see detailed discussion in section 3.1 of this thesis) to examine vertical motions obtained from Doppler radar. This method also relied on spatial uniformity of precipitation being observed by the radar. As such, Cifelli et al. (1996) limited examination of vertical velocity to the stratiform region of tropical mesoscale convective systems. A major contrast to this thesis, the VAD-based methods of divergence and subsequent vertical motion calculations yielded a vertical profile of such parameters at a single point (Figure 2.1). They compared their results from the modified VAD techniques to results obtained from a very-high-frequency (VHF) wind profiler. The VHF profiler frequently observed strong, upper-level divergence and associated upward motion occurring above the top of the single-radar methods’ maximum observable altitude. They concluded that each VAD-based method consistently underestimated the upper-level divergence and therefore upward motion.
The use of multiple Doppler radars can be a powerful tool in analyzing the 3-D wind field. A dual-Doppler network, i.e., two synchronized, spatially separated radars observing the same area, allows for the observation of two radial velocity fields over the same area. This allows, through the relationship between radial velocity and actual velocity, to retrieve a 2-D field of actual velocity. Additionally, vorticity and divergence fields can be calculated and therefore when the mass continuity equation is integrated vertically, a complete 3-D wind field can be obtained (Ray, 1976). Ray et al. (1975) and Ray (1976) used this concept to analyze the structure of a tornadic storm. Using patterns of dual-Doppler-derived divergence and vorticity, they found that they could observe the locations of updrafts and downdrafts as well as a clear, cyclonic circulation.
Subsequent studies involving the use of dual-Doppler observations and the vorticity equation to retrieve boundary conditions for the integration of the mass continuity equation yielded more accurate 3-D wind fields (Mewes and Shapiro 2002, Shapiro et al. 2009).

Later studies took different approaches to calculating the kinematics of Doppler velocity. Smith and Elmore (2004) presented a modified, more robust method for estimating divergent and azimuthal shear (DivShear and AzShear, respectively), expanding on their previous work on the subject. Smith and Elmore (2004) used a 2-D, linear least squares (LLSD) method for calculating DivShear and AzShear. A common, albeit more straightforward, method up to this point relied on a simple difference between the maximum and minimum radial velocities within a feature of interest. This is known as the “peak-to-peak” method. Significant error arose when considering discrete azimuths and beam width relative to the size and position of the feature being sampled (Wood and Brown, 1997). Smith and Elmore (2004) outlined some advantages to using a 2-D LLSD over the traditional peak-to-peak method. The 2-D LLSD was more tolerant of noisy data (typical of radial velocity fields). Additionally, the LLSD removes some of the Doppler dependencies associated with the detection of rotational/divergent features. The divergence algorithm in WDSS-II (w2circ) uses this 2-D LLSD approach (see chapter 3 for more detail on usage of WDSS-II algorithms). An advantage to this technique over those developed by Browning and Wexler (1968) and Cifelli et al. (1996) was the ability to calculate Doppler kinematics over an area instead of at just one point. Additionally, these fields could be visualized using traditional plan-
position indicator (PPI) and/or range-height indicator (RHI) plots. The studies discussed below employed such abilities.

Much of the work done for this thesis involving the use of Doppler-derived divergence is a loose continuation of findings presented in Difani (2016) and Clemins (2018). Difani (2016) attempted to use the Doppler-derived divergence product to discriminate elevated convection from surface-based convection. They identified the need for a radar-based approach for cases in which thermodynamic profiles proved indeterminant. They hypothesized elevated convection would see a lack of convergence at the surface associated with the base of the updraft. Instead, this convergence would be located aloft, just above the thermal inversion. They employed additional storm cell identification techniques to determine the ideal locations for cross sectional analysis of differential reflectivity (ZDR) and divergence. To best approximate the location of the updraft, Difani (2016) used columns of high values of ZDR which nearly correspond to the convective updraft (Illingworth et al., 1987; Brandes et al., 1995; Scarfenberg et al., 2005). With the approximate location of the updrafts known, cross sectional analysis of divergence allowed for the identification of convergence columns associated with the updraft. Figure 2.2, taken directly from Difani (2016) shows a convergence column associated with a convective updraft.
The height of the base of these convergence columns (represented by the star in Figure 2.2) revealed the elevated nature (or lack thereof) of the convection. Using this approach Difani (2016) compared convergence columns associated with elevated and surface-based cases. They identified these cases using observed soundings. The surface-based case was one in which the most unstable CAPE (MUCAPE) was equal to the surface-based CAPE (SBCAPE). The elevated case was one in which the SBCAPE was nonexistent and MUCAPE was sufficient for convective development. They found that the elevated cases had a reduction in near-surface convergence compared to the surface-based cases that was statistically significant. Thus, they concluded that convergence columns could be used to differentiate surface-based convection from
elevated convection. Additionally, they concluded that the characteristics of the convergence columns was representative of the convective updraft.

The work of Clemins (2018) attempted to use plan-view plots of Doppler-derived divergence to aid in the detection of gust fronts. They hypothesized that, since gust fronts are convergence lines, the features would show up well in the divergence (convergence) field. A four-step data processing algorithm was employed in order to isolate and highlight the features of interest. Unconcerned with magnitudes in the final analysis, they chose a convergence/divergence magnitude threshold and applied it to all values meeting that threshold. Secondly, to filter noise and isolate contiguous areas, they applied an aerial threshold to the data. To connect and smooth features of interest, the data was dilated and subsequently eroded. Figure 2.3, taken directly from Clemins (2018) shows this four-step process.
After examining multiple cases from both MZZU and KLSX, Clemins (2018) concluded that plan-view analysis of Doppler-derived divergence could be used to identify and track convective features such as the gust front. The ability to use Doppler-derived divergence to examine convective features and their structure is an integral component of this project and the discussions given in the ensuing chapters.

Figure 2.3 taken from Clemins (2018) showing the four-step process of processing the radar-derived convergence/divergence field. a) is the raw con/div field. In all four subplots, yellow (blue) represents div (con). b) is with a magnitude threshold applied and -1 (+1) subsequently applied to convergence (divergence). c) is the dilated field. d) is the eroded field.
Chapter 3 – Data and Methodology

3.1 – A derivation of an expression for vertical velocity

The following is a brief discussion and derivation to show, mathematically, how radar-derived divergence is useful for assessing vertical motion. Starting with the continuity equation presented in Hess (1959):

\[-\frac{1}{\rho} \frac{d\rho}{dt} = \frac{\partial u}{\partial x} + \frac{\partial v}{\partial y} + \frac{\partial w}{\partial z}\]  

Equation 3.1 states that rate of change in density with time is proportional to the 3-dimensional velocity divergence. If the atmosphere is assumed to be incompressible, the change in density with time will equal 0 (Hess, 1959), thus the equation can be rewritten as:

\[\frac{\partial w}{\partial z} = -\frac{\partial u}{\partial x} - \frac{\partial v}{\partial y} = -\nabla_2 \cdot \vec{V}_2\]  

\[\int_{w_0}^{w} \partial w = -\int_{z_0}^{z} \nabla_2 \cdot \vec{V}_2 \, dz\]  

\[w = -\int_{z_0}^{z} \nabla_2 \cdot \vec{V}_2 \, dz\]  

Which states that the vertical wind (w) can be obtained from a vertical integration of 2-dimensional, horizontal divergence from an initial height \(z_0\) to a higher height \(z\). This thesis took \(z_0\) to be the surface (or 0 m above ground level). At exactly 0 m AGL, \(w\) was assumed to be 0 m/s. With this assumption, the relationship could be expressed by Equation 3.2c. Known as the kinematic method of computing vertical motion, an in-
depth derivation was performed in Panofsky (1946). Subsequent techniques employed this methodology using a weather-balloon-based approach (Bellamy, 1949). For a finite number of layers in the vertical (representative of what a radar yields), \( w \) could be approximated as:

\[
\begin{equation}
 w_{avg} \approx -\frac{\sum (\nabla \cdot \vec{V}) \Delta z}{N}
\end{equation}
\]

Where \( \Delta z \) was the depth of the entire atmospheric column over which the integration was performed, and \( N \) was the number of grid points in the column. A division by \( N \) was necessary since one value for updraft/downdraft magnitude represented the entire column. Equation 3.3 was the premise on which the results discussed in chapter 4 were based. While the assumptions of a hydrostatic, incompressible atmosphere tend to break down on the smaller scales, the divergence associated with the convection will be significantly larger than any density changes resulting from compressibility. So, while not a perfect assumption, changes in density were considered negligible compared to the velocity divergence.

### 3.2 – Data acquisition

The third objective listed in section 1.1 presented this project as a potential, new technique aimed at producing nowcasts of intensity for existing convection. As such, one of the aims of this thesis was to use a purely radar-based dataset to ensure its simplicity and practicality. Data for this project were collected from a Weather Surveillance Radar 1988-Doppler (WSR-88Ds), the Doppler radar used by the National
Weather Service’s Next Generation Weather Radar (NEXRAD) network. NEXRAD Level-II files for WSR-88D data were downloaded directly through the National Center for Environmental Information (NCEI)’s NEXRAD archive. Cases from three common convective modes were explored: ordinary, multicell, and supercell. The latter two cases represented those in which nowcasting convective intensity could be useful.

For orographic continuity, each case was taken from the WSR-88D at the National Weather Service office in St. Louis, Missouri (KLSX). The NEXRAD mosaic archive from Iowa State University proved helpful in analyzing reflectivity over a 24-hour period to find a case of ordinary convection near KLSX. A case of ordinary convection from the afternoon of June 27, 2021, was chosen. The multicell case that was chosen was a squall-line, mesoscale, convective system (MCS) that impacted the St. Louis region on May 21, 2019. As the MCS approached the region, an embedded supercell formed. The cell produced a tornado in St. Charles County near the town of Augusta, Missouri.

The final case, the supercell case, was very well-known around the St. Louis region. On April 22, 2011, thunderstorms formed over mid-Missouri in the late afternoon, developing into twin supercells by the time they approached the far western outskirts of the St. Louis region. The northern cell went through multiple cycling stages, before it rapidly strengthened as it crossed the Missouri River into St. Louis County. The storm produced an EF-4 tornado that impacted St. Louis Lambert International Airport (KSTL).
3.3 Data processing: WDSS-II

The Warning Decision Support System – Integrated Information (WDSS-II) is a collection of tools and algorithms for analysis and visualization of weather radar data. The software was designed and developed by the National Severe Storms Laboratory (NSSL) and the Cooperative Institute of Mesoscale Meteorological Studies (CIMMS) out of the University of Oklahoma. In addition to real-time data visualization, WDSS-II contains a suite of algorithms that generate derived products in both real-time and archived cases (Lakshmanan et al., 2007). Of the many functionalities that WDSS-II carries with it, the divergent shear (DivShear) and azimuthal shear (AzShear) derived products obtained through the w2circ algorithm were of greatest use to fulfill the objectives of this thesis. Once obtained from NCEI, the first step in data processing was to convert the files from NEXRAD Level-II format, to one in which the data could be read, extracted, and manipulated. With the eventual task of reading processed data using Python, the best method was to convert the files to netCDF format. Within netCDF files, multi-dimensional data and metadata are stored in easily referenceable structures. The conversion was done using the WDSS-II ldm2netcdf algorithm. After converting the files, the velocity field needed to be dealiased. The dealiasVel algorithm contained in WDSS-II made this a simple task. Once dealiased, the w2circ algorithm was able to be performed. w2circ computes the divergent and azimuthal shear using a linear least squares (LLSD) method described by Smith and Elmore (2004). In a 2-dimensional, cartesian, coordinate system (x, y), divergence is the change in the directional
components of the wind with respect to each cardinal direction. This is represented by Equation 3.4:

\[
div = \nabla \cdot \vec{V} = \frac{\partial u}{\partial x} + \frac{\partial v}{\partial y}
\]  

(3.4)

Divergent shear, as computed by WDSS, is simply the change in wind speeds along a radial. The nature of radial velocity makes it so that this is the only component of divergence that can be observed by a Doppler radar. Divergent shear is expressed as:

\[
DivShear = \frac{\partial V_{rad}}{\partial r}
\]

(3.5)

The primary issue encountered was DivShear’s Doppler nature. Like, Doppler velocity, it is purely the component along a radial, therefore cross-radial motions are missed. At first, to account for this, a crude directional calculation was performed on the dealiased velocity data. This was done by finding the maximum average radial velocity for a radial over an entire sweep and treating that azimuth as the wind direction. The wind was then adjusted using the angle between the radial and wind direction (\(\theta\)) in accordance with the relation between radial velocity and actual velocity. This relation is given by Equation 3.6:

\[
V = \frac{V_{rad}}{\cos \theta}
\]

(3.6)

With this method, a relatively uniform coverage of hydrometeors is required, a problem if dealing with isolated convection. Additionally, this method introduced excessive sensitivity near the 0-isodop as values there approached infinity. Therefore, a far
simpler method was developed to account for this issue. As the real wind becomes increasingly orthogonal to the radials, the radar is observing less of the real wind field and the radial velocities approach 0. As such, there is horizontal shear that arises from the real wind direction. It was thought that considering the cross radial change in radial velocity, more commonly known as the azimuthal shear, is sufficient for a directional correction. The corrected divergence (CorDiv) is approximated by:

\[
\text{CorDiv} \approx \frac{\partial V_{rad}}{\partial r} + \frac{\partial V_{rad}}{\partial \theta} \approx \text{DivShear} + \text{AzShear} 
\]  

(3.7)

Previous work had determined that azimuthal shear could be used to assess mesocyclone characteristics. The rotation track product created by the NSSL was found to sufficiently track the location and strength of a storm’s mesocyclone (Miller et al., 2012). With AzShear now considered, the corrected divergence is no longer merely consists of one-dimensional shear of radial velocity. Figures 3.1a–d are plan-position

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{figure3.png}
\caption{
Figure 3.1a (left) and Figure 3.1b (right). a) is the uncorrected divergent shear field represented by Eq. 3.5. b) is the corrected divergence field approximated by Eq. 3.7. In both subplots, brown (green) represents divergence (convergence).
}
\end{figure}
indicator (PPI) and range-height indicator (RHI) plots from the April 22, 2011, supercell case of the uncorrected and corrected divergence fields.

Figures 3.1a and 3.1b showed subtle differences between the uncorrected divergent shear and the corrected divergence. Noticeable differences could be seen between figures 3.2a and 3.2b. In the cross section of the corrected field (3.2b), more continuous and coherent updraft and downdraft structures were visible.

Figure 3.2a (top) and Figure 3.2b (bottom). a) is a radar cross section of uncorrected divergence. b) is a radar cross section of corrected divergence. In both subplots, brown (green) represents divergence (convergence).
3.4 Data processing: Python

Though WDSS-II has its own software for data visualization, various Python packages were used to perform the necessary calculations on and subsequently plot the output data. The data were configured to match the format required for use by the Python ARM Radar Toolkit (Py-ART). Py-ART is a package in Python developed and maintained by the Department of Energy’s Atmospheric Radiation Measurement (ARM) Climate Research Facility (Helmus and Collis, 2016) for weather radar analysis. Within Py-ART, there are existing functions that would otherwise be programmatically intense if done from scratch. To achieve the desired data format, preliminary file processing was needed. Though netCDF files are well suited for storing multiple, multi-dimensional data objects and metadata, the WDSS-II ldm2netcdf and w2circ algorithms output each radar variable and their many elevation angles into separate files each in its own subdirectory. The output files are identically named, using a date-time (of volume scan) convention, and put into separate subdirectories organized by elevation angle. This output method was not ideal for bulk file processing. A separate script was written to be run first, reorganizing all of the directories from an elevation-angle-based system to a volume-scan-based system.

At this stage, the data from the separate files were read into the main script, concatenated into one, large, NumPy array, and inserted into a Py-ART radar object. The program was initially developed by performing these steps on data from the University of Missouri’s X-band Doppler radar (MZZU). The scanning strategy that MZZU uses simply forms a volume scan by scanning elevation angles in ascending order. The
datasets from each elevation angle formed arrays with dimensions [360, 560] representing 360 radials each with a range of 560 gates. This made it a fairly simple process to combine all elevation angles and reshape them into an array with dimensions [360*(number of elevations), 560]. This single-array format represented an entire volume scan and was what the Py-ART radar object required. Unfortunately, the data from KLSX were not as elegant. The NWS radars use super resolution scanning in the lowest three elevation angles for level-II data. Rather than 360 one-degree azimuths, super resolution contains 720 half-degree azimuths. Additionally, the lowest elevation angles contained significantly more gates than the higher angles due to a scanning practice called AVSET. To produce a faster volume scan, AVSET will cause the radar to stop scanning in the upper levels when it no longer detects any echoes. For operational use, data at long ranges in the highest elevation angles are of little use. The meant that each elevation angles’ respective arrays were different shapes from one another. This presented an inconvenience as NumPy’s reshape function required that the given array have the exact number of elements needed for the desired new dimensions. For example, if the desired shape was a 3 x 3 array, the given array must have contained nine elements. So, to combine all the elevations’ respective arrays, each needed to be the same dimension. The easiest approach was to trim the largest arrays of the lower levels to match the dimensions of the smallest array. As such, the maximum range at which this method works depended on what the radar was observing in the upper levels. For example: the supercell case from KLSX on April 22, 2011, had a maximum observable range of approximately 75 km after trimming. Likewise, the lowest three
elevations were trimmed from 720 azimuths to 360 azimuths by picking out every other half-degree azimuth and the associated data.

In order to perform the vertical integration described in section 3.1, the corrected divergence field needed to be mapped from a polar coordinate system to a 3-D cartesian coordinate system. In a cartesian coordinate system, the depth of the column of interest ($\Delta z$) was constant and easily known. In a polar coordinate system, this was not the case.

*Figure 3.3a (top) and Figure 3.3b (bottom). a) is a radar cross section of reflectivity in a polar coordinate system. b) is approximately the same cross section location after mapping the data to a cartesian coordinate system. Reds, and pinks, represent the most intense reflectivity echoes*
Figures 3.3a and 3.3b are range-height indicator (RHI) plots of reflectivity compared to a reflectivity cross section in a cartesian framework. It is important to point out that these two cross sections are, spatially, not perfectly collocated. The polar cross section (3.3a) was taken along the 275° azimuth while the cartesian cross section (3.3b) was taken along a latitude slice. There was a clear varying of size of gates in the polar framework while all grid points in the cartesian system were of equal size. Additionally, each grid point was directly atop one another, which made a vertical summation simple. To perform the cartesian mapping, Py-ART’s grid_from_radars function was used. This function took each radar gate and mapped them to a cartesian grid using a radius of influence (Cressman, 1959; Barnes, 1964; Pauley and Wu, 1990; Helmus and Collis, 2016). An adequate spatial resolution was found using grid boxes that were roughly 100 meters x 100 meters in area and 500 meters tall. The gridding was performed with passed parameters that aimed at making the area of the grid boxes comparable to the 250-meter gate width that a WSR-88D produces. However, this resolution appeared too coarse, so the size described above was settled on.

The vertical integration was carried out using a simple summation function. Since all levels in the cartesian framework were of the same size and resolution, this was a simple process. Then, in accordance with Equation 3.3, the sum was multiplied by the total depth that was summed over and divided by the number of grid boxes. The vertical integration was not performed over the entire depth of the radar volume. In the atmosphere, converging air at the surface rises until it reaches the tropopause. The stability associated with the stratosphere means that the tropopause acts like a ceiling.
for rising air. Therefore, rising air diverges upon reaching the tropopause. This was found to be true in cross-sectional analysis of the supercell case. So, if the summation was performed over the entire column depth, divergence aloft would cancel convergence at the surface and lead to an underrepresentation of magnitudes. As such, the summation was performed only up to the climatological level of non-divergence (LND) of approximately 500 hectopascals (AMS Glossary, 2012). The height of the grid box closest to the LND was 5000 meters and represents the Δz term in Equation 3.3.

Similar to the maximum range discussed above, there was also a minimum range at which results vertical velocities could be viewed. Forecasters are used to looking at radar data in the traditional polar framework at levels of constant elevation angles. As the elevation angle increases, the size of the “cone of silence” remains the same as the altitude of that level changes drastically. In a cartesian framework, levels are of constant altitude. Plots of this type are called constant altitude plan position indicators (CAPPIs). With CAPPIs, the “cone of silence” increases in size drastically with altitude. After performing the summation up to 5000 meters, the cone of silence is approximately 30 kilometers in diameter. Therefore, the minimum range at which it is possible to observe updraft structure is half of this number: 15 kilometers. A more robust algorithm could have been developed to deal with this problem, but the computational power that would have been required to loop through all elements of the 3-dimensional arrays would have immense. Furthermore, such an addition would have produced very little benefit as summing below 5000 meters would have been an incomplete sample of the
storm structure. Chapter 4 will discuss the results that the proposed method produces with the supercell, multicell, and ordinary convective cases.
Chapter 4 – Results

Contained in this chapter will be the results from the three cases described in Chapter 3: June 27, 2021 (ordinary), May 21, 2019 (multicell), and April 22, 2011 (supercell). In each convective modes’ respective section, a brief discussion about the structures of the mesoscale updrafts (UDs) and downdrafts (DDs) will be included. This is necessary to gauge whether the presented technique is sufficiently assessing the shapes, sizes, and locations of the UDs and DDs. This will be done by providing side-by-side comparisons of the plan-view plots of vertical motion and reflectivity fields.

4.1 – Ordinary Case

4.1.1 – Structure of ordinary convection

Ordinary convection, also referred to as simply “single-cell convection” consists of only one updraft. Descending air associated with the downdraft, upon reaching the surface, diverges producing a feature known as a gust front. Lift along the gust front associated with these storms is unable to produce subsequent, organized convection (Markowski and Richardson, 2010). Environments that favor ordinary convection are weakly sheared implying weak synoptic forcing. As such, ordinary convection is diurnally driven, e.g., commonly occurring just after maximum daytime heating when CAPE is at a maximum and CIN is at a minimum. Updraft speeds can be as weak as 5 m/s in low-CAPE environments and as high as 40 m/s in high-CAPE environments (Markowski and Richardson, 2010). A “first guess” approximation of maximum updraft speeds falls
naturally out of CAPE. Assuming that, within the updraft, all potential energy is converted to kinetic energy, kinetic energy (KE) can be expressed as:

$$KE = \frac{1}{2}w^2 = CAPE$$  \hspace{1cm} (4.1a)

Where \( w \) is the vertical velocity in a cartesian framework. Thus, Equation 4.1a can be rearranged to obtain an expression for the maximum vertical velocity:

$$w_{\text{max}} = \sqrt{2 \times CAPE}$$  \hspace{1cm} (4.1b)

A more detailed justification for this expression is given by Djuric (1994). Equation 4.1a will be used later on in this chapter to ascertain whether the updraft speeds obtained using the method proposed by this thesis produces magnitudes that correspond to realistic values of CAPE.

The lifecycle of ordinary convection occurs in three stages: towering cumulus, mature, and dissipating stage. The “first” stage, towering cumulus, is characterized by only updraft. Though the preceding cumulus cloud existed before this stage, at this point, the updraft speeds are sufficiently strong to distinguish it from non-thunderstorm, cumulus clouds. The latter part of this stage is typically when echoes first show up on radar (Doswell, 1985). Eventually, hydrometeors suspended by the updraft become too heavy and will fall as rain. The lack of significant vertical wind shear means that these precipitation particles will fall through or in close proximity to the updraft rather than being deposited away from it. The falling precipitation will reduce updraft buoyancy through loading and induce a downdraft through cooling associated with
evaporation and (in the upper levels) melting (Markowski and Richardson, 2010). At this point, the thunderstorm has reached the mature stage and is characterized by the presence of both an updraft and downdraft. The final stage, the dissipating stage, begins as the downdraft undercuts the updraft as it reaches the surface and diverges. This cuts off the warm, unstable air that supplies the updraft (Doswell, 1985). Soon after, the updraft rapidly dies, and the thunderstorm is dominated by only downdrafts. The thunderstorm decays quickly as it “rains itself out” for the remainder of its life. Due to the lack of separation between the updraft and downdraft, this entire lifecycle unfolds rather quickly, lasting only 30 – 60 minutes from the beginning of the towering cumulus stage (Doswell, 1985; Markowski and Richardson, 2010). Figure 4.1, adapted from Doswell (1985) describes the entire process pictorially.

![Figure 4.1](image)

*Figure 4.1a (left), 4.1b (middle), and 4.1c (right) taken from Doswell (1985). a) represents the cumulus stage with vector arrows show the presence of only updrafts. b) represents the mature stage with vector arrows showing the presence of both updrafts and downdrafts. c) represents the dissipating stage with vector arrows showing the presence of only downdrafts.*
4.1.2 – June 27, 2021

During the afternoon of June 27, 2021, classic, summertime, pop-up convection sprang up across central and east-central Missouri. Thunderstorms stayed below severe limits as they were diurnally driven with no apparent synoptic forcing. South of the St. Louis metro, convection was able to merge into a loosely organized multicell cluster. Therefore, though it looked like a well-organized storm in reflectivity, it was ignored for this discussion. Attention was given to the seemingly insignificant cells that popped up and quickly died to the north and west of the St. Louis metro.
Figure 4.2a (top) 4.2b (middle), and 4.2c (bottom) depicting the reflectivity and vertical velocity fields for the 19:58, 20:03, and 20:07 UTC scans respectively. In all subplots depicting the vertical velocity field, red represents updrafts and blue represents downdrafts.
First and foremost, the technique that this thesis is proposing is likely not assessing the vertical velocity magnitudes accurately. Some possible explanations for error are presented in Chapter 5. What the results in this chapter will show is confidence that the technique is however, assessing vertical velocity magnitudes with precision, i.e., the values calculated were repeated, but likely did not represent the true UD/DD velocities. As will be become plain in Sections 4.2 and 4.3, the updraft magnitudes were significantly weaker for the ordinary case than they were for the multicell and supercell cases as expected. Thus, with confidence that the magnitudes are precise, trends (i.e., strengthening or weakening) can be confidently observed. The 19:58 UTC scan (Figure 4.2a) preceded a pop-up cell first showing up on radar. In the reflectivity, nothing could be seen in Illinois north of St. Charles County, Missouri. In the vertical velocity field, there was a very weak updraft and downdraft evident and is circled in Figure 4.2a. In the reflectivity field of the 20:03 UTC scan, the developing convection was still not evident while the vertical velocity field still showed a subtle feature. Finally, in the 20:07 UTC scan, a weak echo showed up in reflectivity. In these scans, take particular notice to how the developing convection already had an observed downdraft associated with it. Recall Section 4.1.1’s discussion of Doswell (1985). A thunderstorm typically first shows up on radar at the very end of the towering cumulus stage where it possesses only updrafts. Thus, one would expect that, by the time it is observable in a complete volume scan, the thunderstorm would be in its mature stage where it possesses both updrafts and downdrafts. Figure 4.3 below shows the short life of this convective cell.
By the 20:35 UTC scan (Figure 4.3f), the updraft could not be seen in the vertical velocity field. In subsequent scans, it was evident that this cell was dying as reflectivity later decreased. Almost the exact same behavior could be observed in the vertical velocities associated with the cell immediately to the west. It developed just as it crossed the Mississippi River into Illinois. It did not show up in reflectivity until the 20:40 UTC scan, but in the vertical velocity field, a feature was seen beginning at the 20:30
UTC scan. It had a much shorter lifespan than its friend to its east, beginning its death after the 20:49 UTC scan. In the 20:59 UTC scan, an updraft could be seen once again as the reflectivity continued to decrease. Subsequent scans (Figure 4.4 below) showed development of a new cell.

![Diagram](image-url)

![Diagram](image-url)
Yet another similar trend could be seen in this cell and new development to its southeast. With similar trends being repeatedly seen in ordinary convection in addition to lining up with the work of Doswell (1985), the technique seems to be doing an adequate job assessing these updraft and downdraft structures. The near upright structure of ordinary convection made this vertical summation technique practical in

Figure 4.4a – 4.4j depicting the reflectivity and vertical velocity fields for the 21:04 through 20:48 UTC scans respectively. In all subplots depicting the vertical velocity field, red represents updrafts and blue represents downdrafts.
such cases. The multicell and supercell cases discussed below revealed some drawbacks to the simple vertical summation.

4.2 – Multicell Case

4.2.1 – Structure of multicell convection

Multicell convection encompasses a wide variety of different “flavors.” In contrast to ordinary convection, multicell convection is characterized by the repeated development of new convective cells along the existing gust front from older, mature cells. Unlike ordinary convection, the lift along the gust front is sufficiently strong for new convective initiation. Figure 4.5, adapted from Doswell (1985) illustrates the subsequent convective initiation and morphology associated with multicell convection.
The continuous development of new cells on a preferred flank leads to an apparent direction of propagation for the complex as a whole (Markowski and Richardson, 2010).

Multicell convection can be categorized as meso-\(\alpha\)-scale convective systems, commonly referred to as simply mesoscale convective systems (MCSs), or meso-\(\beta\)-scale cluster of cells (Markowski and Richardson, 2010). The case discussed in Section 4.2.2 below falls under the classification of an MCS, specifically a squall line with trailing stratiform region of precipitation. As such, the ensuing discussion of multicell structure will pertain to such. Figure 4.6, taken from Houze et al. (1989), is a conceptual model depicting the structure of squall lines with trailing stratiform. They developed this model.
using both single- and dual-Doppler radar observations in addition to aircraft and satellite observations.

As can be seen from Figure 4.6 above, new convective cells form on or ahead of the leading edge of the line. This new development is associated with a strong convective updraft. Immediately behind it is a mature cell and its associated updraft and downdraft cores. Immediately behind that, in this particular model, is an older cell about ready to reach its dissipating stage. Still with the older cell though is its respective updraft and downdraft cores. To add clarity, red arrows and blue arrows representing the updraft and downdraft cores respectively have been superimposed onto the Houze et al. (1989) figure. Not pictured are even older, dissipating cells that are advected backwards by the ascending front-to-rear flow and contribute to the maintenance of the trailing stratiform region (Houze et al., 1989). The gradual ascent associated with the front-to-rear flow

Figure 4.6 taken from Houze et al. (1989) shows a cross section taken perpendicular to a squall-line MCS. Solid streamline arrows represent the general flow within the storms. Red and blue arrows were superimposed onto the image to highlight the individual cells' respective updraft and downdraft regions. The dashed arrows denote how the older convection contributes to the region of trailing stratiform precipitation. The shaded areas represent reflectivity echoes.
can occur over tens of kilometers with weak vertical velocities of less than 0.5 m/s (Markowski and Richardson, 2010). Immediately beneath it is the descending rear inflow which can vary in strength considerably from system to system (Houze et al., 1989). In cases where the descending rear inflow is quite strong, it can cause the leading line of convection to surge forward creating a feature known as a bow echo (Markowski and Richardson, 2010).

### 4.2.2 – May 21, 2019

On the afternoon of May 21, 2019, a quasi-linear convective system (QLCS) moved across the St. Louis County Warning Area (CWA). This squall line produced three brief tornadoes in Callaway County and Franklin County in Missouri and Monroe County in Illinois. The line largely came within the vertical velocity range near 21:50 UTC and thus was the start of this discussion.
Figure 4.7a – 4.7d depicting the reflectivity and vertical velocity fields for the 21:50 through 22:13 UTC scans respectively. In all subplots depicting the vertical velocity field, red represents updrafts and blue represents downdrafts.
The first tornado occurred near Yucatan, MO in Callaway County just as the northernmost part of the line came into range. The vertical velocity field (Figure 4.7a) did not look overly impressive. Strongest magnitudes remained to the south over central Missouri. In Callaway County, however, there were discontinuities in the UD/DD structures. Where in the south, the structures were obviously linear, the northern structures were more characteristic of rotational couplets from the very beginning (21:50 UTC scan). These couplets persisted in subsequent scans despite the line looking more linear in the reflectivity field. The storm dropped a brief tornado closest to the 22:05 UTC scan. By the 22:13 UTC scan, the individual couplets became less evident and even began to look more linear. This trend implied a decrease in the tornadic threat associated with the northern part of the line despite the couplets that were still present in the base velocity field at 22:13 and 22:20 UTC (Figure 4.8a and 4.8b).
Figure 4.8a and 4.8b are the base velocity fields taken from GR2Analyst for the 20:13 and 20:20 UTC scans respectively. In both figures, the red polygon is the tornado warning issued by the NWS. These two base velocity scans are at the same times as the fields in Figure 4.7d and Figure 4.9a respectively.
Much of the focus for the multicell case was given to the central part of this line. In the 22:20 UTC scan (Figure 4.9a), there was a noticeable kink in the line in the vertical velocity field. In the reflectivity field at this same time, there was a much less subtle “notching” that occurred in northwest Crawford County and southwest Franklin County. The kink became more evident in the vertical velocity field of the next scan but remained subtle in reflectivity. This notching of the UD and DD structures implied that the storm was taking on a more rotational behavior. At this point, no easily discernable rotation was evident in the base velocity field (Figure 4.10).

*Figure 4.9a and 4.9b depicting the reflectivity and vertical velocity fields for the 22:20 and 22:27 UTC scans respectively. In all subplots depicting the vertical velocity field, red represents updrafts and blue represents downdrafts. The fields in a) are at the same time as the base velocity field in Figure 4.8b.*
Figure 4.10 showing the base velocity field for the 20:20 scan this time focused on the southern portion of the MCS. The base velocity field is taken at the same time as the fields shown in Figure 4.9a.
Figure 4.11a – 4.11d depicting the reflectivity and vertical velocity fields for the 22:35 through 22:57 UTC scans respectively. In all subplots depicting the vertical velocity field, red represents updrafts and blue represents downdrafts.
The notching became much more evident in reflectivity between the 22:35 and 22:50 UTC scans (Figure 4.11a—c). Simultaneously, there was a slight increase in the vertical velocity magnitudes as they jumped from the 30 m/s range to the 40 m/s range. These signs pointed towards a gradually strengthening storm and by the 22:50 UTC scan, an embedded supercell had become more apparent in the reflectivity. In between this and the 22:57 UTC scan, the storm produced a short-lived EF-1 tornado that crossed the Missouri River from Franklin County to St. Charles County (NWS St. Louis). Just before the storm moved into the large “cone of silence” in the vertical velocity field, a significant jump in DD magnitude was observed. Unfortunately, with the lack of data, it was unclear if this could be associated with the presence of the tornado. Additionally, there was another kinking feature to the south that first became apparent in the vertical velocity field over Washington County in the 22:50 UTC scan. Slight notching could be seen in the reflectivity in the next scan (Figure 4.11d).
The kink in the vertical velocity field of the 23:11 UTC scan (Figure 4.12b) faded. While this storm did not produce a tornado at this time, the bending of the linear UDs and DDs was evident two entire volume scans before it became apparent in reflectivity.
Figure 4.13a and 4.13b depicting the reflectivity and vertical velocity fields for the 23:33 and 23:40 UTC scans respectively. In all subplots depicting the vertical velocity field, red represents updrafts and blue represents downdrafts.

Skipping several uninteresting volume scans, Figure 4.13 shows the 23:33 and 23:40 UTC volume scans. An interesting number of features showed up in Jefferson County in these scans. Recall Figure 4.6 taken from Houze et al. (1989). As discussed in Section 4.2.1, squall lines propagate due to the constant development of new convective cells near the outflow. Older cells and their respective UD and DDs go through their respective
lifecycles behind the new convection. Especially evident in the 23:33 UTC scan were separate areas of upward and downward motion over Jefferson County that were oriented northwest to southeast. This was orthogonal to the individual cells’ motions (not to be confused with the MCS propagation). The results appeared to be following Houze et al. (1989)’s conceptual model quite well. Similar, albeit less defined, structures could be seen throughout the squall line’s march across the observed area.
At approximately 00:01 UTC, the squall line produced a very brief, spin-up tornado in Waterloo, IL (NWS St. Louis). The scans leading up to this time did not contain any obvious strengthening trends. Neither the structure nor the magnitudes of the UDs and DDs showed any apparent strengthening trend. The more interesting feature came out of southwestern Lincoln County in Missouri. The subtle changes from weak downward motions to weak upward motions over the county was a possible gravity wave that the technique observed well.

Overall, the structure of the MCS was likely being observed well. Chapter 5 offers an in-depth discussion regarding potential error in the placement of the UDs and DDs for all cases. Regardless, the kink that showed up in the vertical velocity field prior to evident rotation in the base velocity is promising for applying this to nowcasting. The average maximum updraft speeds over the course of the scans discussed was approximately 35 m/s. Using equation 4.1a, this corresponded to a CAPE of about 600
J/kg. While this value seemed rather low for this type of event at this time of year, observed soundings out of Columbia, Missouri prior to the passage of the MCS showed a preconvective environment with only about 300 J/kg of most unstable CAPE.

4.3 – Supercell Case

4.3.1 – Structure of supercell convection

A supercell is characterized by “a single, quasi-steady, rotating updraft that persists for a period of time much longer than it takes an air parcel to rise from the base of the updraft to its summit” (AMS Glossary, 2012). For the supercell’s updraft to persist, in contrast to ordinary convection, the updraft must be horizontally separated from the downdraft. This allows the updraft to continually ingest warm, moist air without being choked by the rain-cooled air associated with the downdraft. For this to occur, the convective environment must have sufficient vertical wind shear. The separation of the UD and DD will lead to a well-established structure unique to supercell thunderstorms first analyzed by Browning (1962, 1964).

As mentioned above, the defining feature of a supercell is its single, persistent, rotating updraft. Occasionally, a flanking line of updrafts can be seen along the right-rear flank (with respect to storm motion) that are shallower and weaker than the dominant updraft inside of which vertical wind speeds can exceed 50 m/s (Markowski and Richardson, 2010). The flanking line of UDs will usually lead to subsequent convective development. Figure 4.15, adapted from Doswell and Burgess (1993), illustrates the dominant updraft and the flanking line relative to areas of precipitation.
In contrast to the single updraft, supercells contain two prominent downdraft regions. The first is referred to as the rear-flank downdraft (RFD). There is still uncertainty as to whether the RFD is primarily thermodynamically or dynamically forced. Mid- to upper-level, dry winds entrain into the backside of the updraft leading to evaporative cooling and negative buoyancy. Additionally, downward-directed pressure gradients in the vertical likely play a role (Markowski and Richardson, 2010). The second downdraft region is known as the forward-flank downdraft (FFD). The FFD arises from deep-layer shear and mid-level storm-relative winds and their tendency to deposit the bulk of hydrometeors into the forward flank of the updraft. Evaporation of liquid water and
melting of ice in this region results in strong negative buoyancy. Working together, the FFD and RFD produce gust front structures similar to that of a mid-latitude cyclone. In Figure # above, the RFD and FFD are denoted as how a cold front and stationary front would be on a synoptic-scale surface map, respectively. Figure 4.16 shows the same structures from a three-dimensional perspective.

*Figure 4.16, taken from Lemon and Doswell (1979) showing a three-dimensional view of the same structures shown in Figure 4.15. Assuming the same orientation as the supercell from Figure 4.15, this perspective is from the southeast of the storm. The motions associated with the UD and DDs are represented by black streamline arrows. Storm-relative, upper-level motions are represented by the thick shaded streamline arrows. The downdraft leading edges are given by the black “cold fronts”.*
4.3.2 – April 22, 2011

On the evening of Friday April 22, 2011, two supercell thunderstorms moved due east across the St. Louis CWA. Of the two storms, the greatest attention was given to the northern storm as it produced an EF-4 tornado in northern St. Louis County in the suburb of Bridgeton. As mentioned in Section 3.4 the maximum observable range for this case after processing the data was roughly 75 km from the radar. While these storms formed west of Columbia, MO earlier in the afternoon, this discussion covered their lifespan while they were within this range. The two tornadoes that the northern storm produced occurred within this range. Figure 4.17 below shows the surveyed tornado tracks from this northern storm.

![Image of tornado tracks](image)

*Figure 4.17 is the path that the tornadoes took through the St. Louis Metro on April 22, 2011, is given by yellow lines. The location of the KLSX radar is denoted by the red circle. This image was produced in Google Earth using the damage survey KML file courtesy of NWS St. Louis.*
The entirety of the northern storm (henceforth referred to as cell 1) came within range at 23:29 UTC (Figure 4.18). Right away, it could be seen that relatively strong updraft and downdraft magnitudes were being observed. That being said, these values were in line with the magnitudes that Markowski and Richardson (2010) claim are common with strong supercell updrafts. As the storm moved further east in the figures below, the ensuing discussion paid particularly close attention to both the intensity and structure of the features that represented the updrafts and downdrafts.

Figure 4.18 depicts the reflectivity and vertical velocity fields from the 23:29 UTC scan. In the subplot depicting the vertical velocity field, red represents updrafts and blue represents downdrafts.
Figure 4.19a—4.19c depicts the reflectivity and vertical velocity fields from the 23:33 through 23:42 UTC scans respectively. In all subplots depicting the vertical velocity field, red represents updrafts and blue represents downdrafts.
Looking forward to the next three volume scans (Figure 4.19 above), there was an evident breakdown in the coherent structures to the UD and DD cores. This suggested a very-short-term trend of disorganization within the storm. Conversely, there was an increase in reflectivity in the precipitation core of the supercell. This increase in the intensity of the precipitation core occurred after a maximum magnitude of the UDs and DDs was observed in the first volume scan (Figure 4.18). Unfortunately, the storm had just come within range so it was tough to assess whether this increase in precipitation intensity could be correlated with a jump in the UD/DD magnitudes or the coherency to the structure.

![Image](image_url)
In the set of volume scans between 23:46 and 23:55 UTC (Figure 4.20), a slight weakening trend in the maximum reflectivity in the core of the storm could be seen. Interestingly, this occurred after the 23:42 UTC scan (Figure 4.19c) showed an evident drop in UD magnitudes into the upper 20 m/s range. It is important to note that the exact magnitudes should not be treated as accurate for a number of reasons. Recall from Section 3.4 that these data were mapped to a cartesian grid in which data were interpolated. The lowest altitude of the grid was 0.0 kilometers while the radar beam of the 0.5° elevation would be several hundred meters above this. A more detailed discussion of potential sources of error is found in Chapter 5. By the 23:55 UTC scan, the structure regained some coherency. In the subsequent scans (Figure 4.21 below), both the structure and magnitudes began to look more impressive.
Figure 4.21a—4.21c depicts the reflectivity and vertical velocity fields from the 23:55 through 00:03 UTC scans respectively. In all subplots depicting the vertical velocity field, red represents updrafts and blue represents downdrafts.
Between the 23:50 and 00:03 UTC scans, the supercell transitioned from rotationally dominant to divergently dominant, i.e., the cell began to lose its prominent hook echo feature. This came after the vertical velocity of the previous scans, specifically 23:46 and 23:50 UTC, showed several small UD/DD clusters (implying less organization). Then, as the cell lost its hook echo, the clusters seen in the vertical velocity field started to coagulate. By the 00:03 UTC scan the hook echo has almost completely disappeared from the reflectivity field while, in contrast, the vertical velocity field had gained remarkable organization. Figure 4.22 below is the 00:03 UTC scan again, with lines representing the edges of the downdrafts superimposed on the images.

![Figure 4.22](image)

*Figure 4.22 is the same as Figure 4.21c only this time with thick blue lines superimposed on top of the downdraft structures to illustrate the impressive structure matching well with Doswell and Burgess (1993).*

Notice the similarities between the structure of these downdrafts and those depicted in Figure 4.15 by Doswell and Burgess (1993). Of all the scans from this case, the 00:03 UTC field was structurally most impressive. That being said, similar, albeit less defined, structures could be identified throughout cell 1’s lifespan. In the coming scans
represented by Figure 4.23 below, the well-defined structure in the vertical velocity field broke down slightly, but the magnitudes increased significantly. Simultaneously, the hook echo rapidly returned in the reflectivity field.
Referring back to Figure 4.17, the 00:16 UTC scan represents the time at which the tornado first touched down in western St. Charles County. In this case, immediately after the storm attained its most impressive UD/DD structure, the storm began to become rotationally dominant again and the magnitudes jumped into the 60 m/s range. This happened just before the storm dropped its first tornado of the evening. As could be seen from the tornado track in Figure 4.17, this first tornado was short lived, only staying on the ground for approximately 12 km. It could be seen in the 00:16 UTC scan that, once the tornado was on the ground, there was a notable decline in vertical velocity magnitudes. Unfortunately, after this scan, much of the storm entered the cone of silence, so inferring that this was indicative of weakening of the tornado is not wise.

While in the cone of silence, the storm cycled again, not producing another tornado until 00:55 UTC when it just exited the cone of silence and crossed the Missouri River into St. Louis County.
As it came out of the cone of silence, the vertical velocity magnitudes were over 60 m/s again. If the storm was not inside of the cone for the previous two scans, it is possible that a rapid increase in magnitudes could have been noted similar to what was seen prior to the 00:16 UTC scan (Figure 4.23c). For the remainder of its trek through St. Louis County, the storm had a fairly long-track tornado on the ground.

Figure 4.24 depicts the reflectivity and vertical velocity fields from the 00:55 UTC scan. In the subplot depicting the vertical velocity field, red represents updrafts and blue represents downdrafts.
Figure 4.25a—4.25c depicts the reflectivity and vertical velocity fields from the 00:59 through 01:08 UTC scans respectively. In all subplots depicting the vertical velocity field, red represents updrafts and blue represents downdrafts.
As the tornado was on the ground intensifying, the vertical velocity magnitudes kept increasing as well. The maximum downdraft magnitude reached an impressive 109 m/s by the 01:03 UTC scan (Figure 4.25b). Again, as mentioned earlier, while the exact magnitudes should be taken with a grain of salt, the fact that the values were the highest yet seen is likely significant. Figure 4.26 below is the vertical velocity field for the 00:59 UTC scan again. This time, a black cross representing the location at which the NWS surveyed EF-4 damage from this tornado is superimposed on the image.

Figure 4.26 is the vertical velocity field from Figure 4.25a with a black cross superimposed upon it. The black cross represents the small area at which the NWS surveyed EF-4 damage.
The peak intensity of the tornado occurred in between the 00:59 and 01:03 UTC scans (Figures 4.25a and b), when the vertical velocity magnitudes were at their strongest yet seen. The peak updraft speed of 78 m/s corresponded to a CAPE of approximately 3100 J/kg. This was a large, but not uncommon value for CAPE in supercell environments. The tornado maintained an EF-3 intensity for a short period of time and weakened to an EF-2 sometime between the 01:03 and 01:08 UTC scans (Figures 4.25b and c). The tornado retained EF-2 intensity until shortly after it crossed the Mississippi River where it dissipated in Illinois.
Figure 4.27a—4.27e depicts the reflectivity and vertical velocity fields from the 01:12 through 01:29 UTC scans respectively. In all subplots depicting the vertical velocity field, red represents updrafts and blue represents downdrafts.
Between the 01:25 and 01:29 UTC scans (Figures 4.27d and e), the tornado dissipated in Illinois. After the magnitudes dropped off considerably, there was no discernable weakening or strengthening trend observable in the vertical velocity field. This corresponded well with the continuation of EF-2 intensity for the remainder of the tornado’s life. Cell 1 went on to produce another tornado south of Interstate 70 near Highland, IL, beyond the maximum range of the vertical velocity field.

Meanwhile, trends in structure and intensity of the UD and DDs associated with the southern cell (cell 2) were more difficult to observe. Just as it came into view (Figure 4.23b), the UD/DD structure of cell 2 looked somewhat disorganized, but still possessed supercellular characteristics (i.e., RFD and FFD). Vertical velocity magnitudes were modest as they remained in the 40-50 m/s range. As cell 1 emerged from the cone and moved across St. Louis County, cell 2’s motion became increasingly orthogonal to the radar radials. This is likely why it took on a messier look in the vertical velocity field while it simultaneously looked more impressive in the reflectivity field. Regardless, cell 2 did not produce a tornado until it crossed into Illinois near the town of Waterloo. This was a very brief tornado, occurring between the 01:46 and 01:54 UTC scans (Figures 4.28d through f). Even still, the vertical velocity field looked neither well-organized nor intense.
It was likely that no prolonged, coherent structure characteristic of a classic supercell took shape with cell 2 due to its motion in relation to the radar. Where cell 1’s motion was more directly towards KLSX, cell 2’s motion, being much further to the south, was at an angle ranging from 225° (southwest) to 135° (southeast) for the duration of its journey across the area. Even though azimuthal shear was added to the divergent shear to combat this issue, there are still signs that this was insufficient. Notice in any of the vertical velocity fields above, there were subtle upward motions to the south of the radar and downward motions to the north of the radar associated with ground clutter and noise. For this technique to perform adequately on storms taking any path across the observable area, a more robust correction for actual velocity needs to be explored. Overall, the magnitude of the maximum average updraft speed observed per scan was 47 m/s. This corresponded to a CAPE value of approximately 1100 J/kg, reasonable magnitudes for vertical velocity.
Chapter 5 – Discussion and Conclusion

The goal of this project was to determine if a vertical integration of radar derived convergence and divergence could be used to obtain information on a thunderstorm’s updrafts and downdrafts. The project looked at three cases representing the three common convective modes: ordinary, multicell, and supercell. From the results of these three cases, it can be concluded that this technique can be used in this way with some limitations kept in mind. The discussion below will cover these limitations, offer some speculation on why they exist, and what they mean for operational use of this product.

5.1 – Reasons for error

The first problem with the results presented in Chapter 4 is the location of the updrafts and downdrafts in relation to each other. A closer look at the results from the multicell and supercell cases reveal that the locations of the updrafts and downdrafts do not match the established conceptual models discussed in that chapter. In both of these cases, the downdrafts were observed ahead of the updrafts. In both multicell and supercell convection, the updrafts occur in front of the downdrafts behind them. This should be expected as the updrafts need a constant supply of warm, unstable air to maintain themselves. If the downdrafts existed in front of them, the updrafts would quickly choke, and convection would never be able to sustain itself beyond the 30-60-minute period common of ordinary convection (Doswell 1985). So why are the results seemingly the opposite of what they should be? There are two problems that may be affecting the results. First, multicell and supercell convection, unlike their ordinary
counterpart, are dependent on the existence of strong vertical wind shear. The vertical wind shear will act to tilt the updraft and downdraft structures in three dimensions. For this reason, it is likely that a strictly vertical summation is not sampling the entire structures. It is even likely that the vertical summation could be sampling the updraft at the surface but sampling the downdraft aloft. Fortunately, this issue could theoretically be rectified by implementing a much more rigorous process for performing the vertical, or rather, “slanted” integration. The second issue is more complicated. Though Equation 3.2c states, from a purely mathematical sense, that convergence (divergence) contributes to a positive (negative) w, this may not always be the case in the physical atmosphere. The only place in the atmosphere where convergence will certainly contribute to upward motion is the surface as mass cannot penetrate the ground. As air converges aloft, mass theoretically has the opportunity to both rise and fall. These two issues could be contributing towards erroneous results.

Other possible sources of error come from the nature of Doppler radar itself. First, in all cases, a subtle divide exists in the vertical velocity field between upward and downward motions not unlike the divide commonly observed between inbound and outbound velocities in a base velocity field. This leads to the belief that there is still some influence from an “incomplete” 2-D wind field. This likely led to the decrease in vertical velocity magnitudes and the breakdown in coherent UD/DD structures associated with the southern cell (cell 2) in the supercell results. This happened as cell 2 moved increasingly perpendicular to the radar radials where less of the actual velocity would be expected to compose the radial velocity. Section 3.3 discussed an attempt at
making this correction by adding the azimuthal (cross-radial) shear to the divergent (along-radial) shear after a preliminary attempt involving correcting for angle between the true wind direction and radial wind direction proved too sensitive near the 0-isodop. This resulted in a significant overestimation of divergence where the values approached 0. As mentioned briefly in Section 4.3.2, a better correction for actual wind direction could be explored. Second, within a particular radar gate, the radar beam is likely sampling a combination of both updraft and downdraft and a turbulent area between them. This results in a smoothing of small features and is even more true when dealing with cartesian grid points. Lastly, another source of error common with any radar is attenuation. Though this study presented cases solely from an S-band radar, for this technique to be used for shorter wavelengths (e.g., X-band), the effects of attenuation will play a much larger role. The result is a velocity field that is much noisier than that of an S-band radar thus making a clean divergence field harder to obtain. As such, if using the technique on X-band data, divergence values will likely be overestimated.

5.2 – Operational potential

Despite the issues in the current results, the vertical velocity product still has significant operational potential. The results from the three cases show that observing temporal trends in the structural organization and magnitudes of the vertical velocities can reveal information of the behavior of the storm in the very near future. Though the placement of the updrafts and downdrafts do not line up with the conceptual models presented by Doswell (1985), they still appear to follow close the expected shapes of UDs and DDs. The supercell results show that in scenarios where the cell undergoes
cycling, UD/DD structure breaks down before weakening occurs, then becomes well
organized again before rapid strengthening can be observed in reflectivity and other
fields. The multicell results show that a kink in the linear structures of the vertical
velocity field before signs of rotation are obvious in the base velocity or reflectivity
fields. In both of these cases, these trends could be observed immediately preceding
confirmed tornadoes.

It is important to point out that results thus far show that this technique should
not be used to observe updraft and downdraft speeds directly. Though all of the results
presented in Chapter 4 correspond to realistic values of CAPE (and therefore are
theoretically plausible), the potential reasons for error leave too much room for
inaccurate values. As such, the actual speeds should in no way be taken as accurate.
However, there is confidence that the values are precise. The strongest magnitudes are
seen in the supercell case while the weakest are seen in the ordinary case as expected.
Additionally, the magnitudes are at their strongest when the storms were at their
strongest. So, temporal trends in the speeds to assess potential strengthening or
weakening can be reasonably used.

5.3 – Future work

First, analyses of more cases beyond these three would be welcomed. The scope
of this project was simply to develop a preliminary technique to see what, if any,
nowcasting practicalities it may add. Now that the results show promise for operational
nowcasting, a look at more cases would be advantageous. Specifically, cases that had
confirmed tornadic activity associated with them should be a priority. Since this technique does not involve dual-polarization data, the cases available for analysis are potentially numerous as the NEXRAD base velocity product has remained largely unchanged since its inception. A deep statistical analysis using results from this proposed product in consort with confirmed tornado strength could be looked at to see if there is any correlation between the magnitudes and tornado intensity. A thorough statistical analysis of the results compared to the preconvective environment in which the storms formed could provide insight into the accuracy of the magnitudes.

Lastly, there is much future work that could be performed in an effort to improve the technique by minimizing potential error. As mentioned earlier, the results could benefit from a more robust correction for actual velocity. Additionally, a more complicated computation of vertical motion beyond a simple vertical summation would provide a better sample of three-dimensionally tilted structures.
Appendix A – Soundings

Observed soundings from Columbia, Missouri on May 21, 2019. Reproduced in SHARPpy.
Appendix B – Python Code

Python code used to analyze and plot radar reflectivity and divergence data.

The first script was written to rearrange file directories so that each file associated with the same volume scan was in a single directory. The second script was written to read the files for an entire volume scan and perform the vertical summation to calculate the vertical velocity fields.

Script 1:

```python
#%% Changing filenames and copying to one respective directory so WDSS-to-PyART script can work
import os
import shutil

# Make sure to Change 'path' depending on what data you want to process
path = 'C:\Users\Evan\Desktop\Thesis Work\wdss-files\20210627\wdss_netcdf\Circ\DivShear'
os.chdir(path)
shutil.rmtree(path + '\.working', ignore_errors=True)
folders = os.listdir()

# Looping through each angle-based subdirectory
for i in range(len(folders)):
    os.chdir(path + '\' + folders[i])  # Going into the angle subdirectory
    for filename in os.listdir():
        if filename.endswith('.netcdf'):
            os.makedirs(path + '\' + filename[0:15] + '_All', exist_ok=True)
            os.rename(filename, folders[i] + '_' + filename[0:15] + '.netcdf')  # Renaming files
            shutil.move(src=os.getcwd() + '\' + folders[i] + '_' + filename[0:15] + '.netcdf',
                        dst=path + '\' + filename[0:15] + '_All')  # Moving the renamed files
        continue  # Continue statement so it only moves one timestep at a time

# Going back to the parent directory
os.chdir(path)

# Removing the now empty angle-based subdirectories
for i in range(len(folders)):
    os.rmdir(path + '\' + folders[i])
```
Script 2:

```python
import netCDF4 as nc
import numpy as np
import os
import pyart as pt
import matplotlib.pyplot as plt
import cartopy.crs as ccrs
import cartopy.feature as cfeature
import cartopy.io.shapereader as shpreader

# %% Some Definitions that will be useful

def open_netcdf(file, field):
    cdf = nc.Dataset(file)
    data = cdf[field][:]
    return data

def get_lat_long(file):
    cdf = nc.Dataset(file)
    lat = cdf.Latitude
    long = cdf.Longitude
    return lat, long

def get_radar_info(file):
    cdf = nc.Dataset(file)
    elev = cdf.Elevation
    RangeToFirstGate = cdf.RangeToFirstGate
    height = cdf.Height
    time = cdf.Time
    return elev, RangeToFirstGate, height, time

def get_attribute(file, name):
    cdf = nc.Dataset(file)
    attr = cdf.getncattr(name)
    return attr

# %% Defining our working directory and pulling the filenames we are working with

filetime = '20210627-215721_All'
path = 'C:\Users\Evan\Desktop\Thesis Work\wdss-files\20210627\wdss_netcdf\Circ'
os.chdir(path + '\DivShear' + filetime)
os.getcwd()

files = []
for filename in os.listdir():
    if filename.endswith('.netcdf'):
        files.append(filename)
```

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number_of_angles = len(files)

# %% Formatting the data

print('nReading Files...n')
#
# Opening files and extracting number of azimuths and gates per azimuth depending on MZZU or a WSR-88D. These will be our index bounds

gate_range = len(open_netcdf(files[0], 'DivShear')[0, :])
azimuths = open_netcdf(files[0], 'Azimuth')
radials = len(azimuths)

# Creating a list of DivShear fields and azimuths corresponding to each elevation
DivShear = []
azimuth_angles = []
for i in range(number_of_angles):
    DivShear.append(open_netcdf(files[i], 'DivShear'))
azimuth_angles.append(open_netcdf(files[i], 'Azimuth'))

# If the lowest angles are super resolution, i.e., 720 radials they need to be reduced to 360
# Data
low_res = []
for i in range(len(DivShear)):
    if len(DivShear[i]) == 720:  # If statement so it will work with 360 radials
        temp_array = np.array([])
        for j in range(0, radials, 2):  # looping through, iterating by 2
            temp_array = np.append(temp_array, DivShear[i][j, :])
        temp_array = np.reshape(temp_array, [360, int(len(temp_array) / 360)])
        low_res.append(temp_array)
    else:
        low_res.append(DivShear[i])
DivShear = low_res

# Azimuths
low_az = []
for i in range(len(azimuth_angles)):
    if len(azimuth_angles[i]) == 720:
        temp_array = np.array([])
        for j in range(0, radials, 2):
            temp_array = np.append(temp_array, azimuth_angles[i][j])
        low_az.append(temp_array)
    else:
        low_az.append(azimuth_angles[i])
azimuth_angles = low_az
# Cutting down the range to the size of the smallest array. We want all
arrays to be the same size

```
low_range = []
good_gates = DivShear[-2].shape[1] # This will need changing depending
on shape of data at highest angle
for i in range(len(DivShear)):
    if DivShear[i].shape[1] >= good_gates:
        temp_array = np.array([])
        for j in range(good_gates):
            temp_array = np.append(temp_array, DivShear[i][j:j])
        temp_array = np.reshape(temp_array, [360, good_gates],
        order='F')
        low_range.append(temp_array)
    else:
        #low_range.append(data[i])
        continue

DivShear = low_range
```

# Now repeat for the AzShear files

```
os.chdir(path + '\\AzShear\' + filetime)
AzShear = []
for i in range(number_of_angles):
    AzShear.append(open_netcdf(files[i], 'AzShear'))

# If the lowest angles are super resolution, i.e., 720 radials they
need to be reduced to 360
# Data
low_res = []
for i in range(len(AzShear)):
    if len(AzShear[i]) == 720: # If statement so it will work with 360
        radials
        temp_array = np.array([])
        for j in range(0, radials, 2): # looping through, iterating by
        2
            temp_array = np.append(temp_array, AzShear[i][j:j])
        temp_array = np.reshape(temp_array, [360, int(len(temp_array)/360)])
        low_res.append(temp_array)
    else:
        low_res.append(AzShear[i])
AzShear = low_res
```

# Cutting down the range to the size of the smallest array. We want all
arrays to be the same size

```
low_range = []
good_gates = AzShear[-2].shape[1] # This will need changing depending
on shape of data at highest angle
```
for i in range(len(AzShear)):
    if AzShear[i].shape[1] >= good_gates:
        temp_array = np.array([])
        for j in range(good_gates):
            temp_array = np.append(temp_array, AzShear[i][:,j])
        temp_array = np.reshape(temp_array, [360,good_gates], order='F')
        low_range.append(temp_array)
    else:
        #low_range.append(data[i])
        continue

AzShear = low_range

good_angles = len(DivShear)  # Number of angles that are actually full of good data

# Now we want to take that list of arrays and mush it into one array for PyArt functions
full_DivShear = np.array([])
full_AzShear = np.array([])
azimuth_layers = np.array([])
for i in range(good_angles):
    full_DivShear = np.append(full_DivShear, DivShear[i])
    full_AzShear = np.append(full_AzShear, AzShear[i])
    azimuth_layers = np.append(azimuth_layers, azimuth_angles[i])

full_DivShear = np.reshape(full_DivShear, [360*good_angles, good_gates])
full_AzShear = np.reshape(full_AzShear, [360*good_angles, good_gates])

full_DivShear[full_DivShear<=-1] = 0
full_AzShear[full_AzShear<=-1] = 0

# Add DivShear and AzShear to correct radial divergence
cor_div = full_DivShear + full_AzShear

#%% Working with the data
radar = pt.testing.make_empty_ppi_radar(good_gates, 360, good_angles)
lst, lng = get_lat_long(files[0])

# Populating the radar object with info from the WDSS netcdf file(s)
radar.latitude['data'] = np.array([lat])
radar.longitude['data'] = np.array([lng])
radar.range['data'] = np.linspace(int(get_radar_info(files[0])[1]), int((open_netcdf(files[0], 'GateWidth'))[0]*(good_gates-1)+(get_radar_info(files[0])[1][1])), int(good_gates))
radar.azimuth['data'] = azimuth_layers
radar.altitude['data'] = np.array([get_radar_info(files[0])[2]])

fixed_angles = np.array([])  # fixed_angle is a list so need a loop to pull/append them
for i in range(good_angles):
    fixed_angles = np.append(fixed_angles, float(get_radar_info(files[i])[0]))

radar.fixed_angle['data'] = fixed_angles
radar.metadata['instrument_name'] = get_attribute(files[0], 'radarName-value')
radar.time['units'] = str('seconds since ' + filename[6:10] + '-' + filename[10:12] + '-' +
                        + filename[17:19] +
                         ':' + filename[19:21] + 'Z')

elev = np.array([fixed_angles]*360).squeeze()
elev = np.reshape(elev, [360*good_angles,], order='F')
radar.elevation['data'] = elev

# Putting data into a dictionary matching the PyART radar fields format
# DivShear
DivShear_dict = dict([('coordinates', 'elevation azimuth range'),
                      ('data', np.array([])),
                      ('long_name', 'DivShear'),
                      ('standard_name', 'divergent_shear'),
                      ('units', '1/s')])
DivShear_dict['data'] = full_DivShear
radar.fields = {'DivShear': DivShear_dict}

# AzShear
AzShear_dict = dict([('coordinates', 'elevation azimuth range'),
                     ('data', np.array([])),
                     ('long_name', 'AzShear'),
                     ('standard_name', 'azimuthal_shear'),
                     ('units', '1/s')])
AzShear_dict['data'] = full_AzShear
radar.add_field('AzShear', AzShear_dict)

# Total Divergence
cor_div_dict = dict([('coordinates', 'elevation azimuth range'),
                     ('data', np.array([])),
                     ('long_name', 'CorDiv'),
                     ('standard_name', 'Corrected_radial_divergence'),
                     ('units', '1/s')])

cor_div_dict['data'] = cor_div
radar.add_field('CorDiv', cor_div_dict)
# The radar object now contains everything it needs to perform PyART functions

tot_range = radar.range['data'][-1]

#%% Plotting the Polar coordinate data
""
projection = ccrs.LambertConformal(central_latitude=radar.latitude['data'][0],
central_longitude=radar.longitude['data'][0])
display = pt.graph.RadarMapDisplay(radar)
fig, ax =
plt.subplots(subplot_kw={'projection':projection},**{'figsize':[12,10]})
display.plot_ppi_map('CorDiv', embelish=False, vmin=-0.02, vmax=0.02,
                     projection=projection, resolution='10m',
                     cmap='BrBG_r',
                     shapefile='C:\Users\Evan\Desktop\Thesis Work\\MO_2018_County_Boundaries.shp',
                     shapefile_kwargs={'facecolor':'none',
                                      'edgecolor':'gray'},
                     lat_0=(radar.latitude['data'][0]),
                     lon_0=(radar.longitude['data'][0]))
plt.show()

xsect = pt.util.cross_section_ppi(radar, [275])
display2 = pt.graph.RadarDisplay(xsect)
fig, ax = plt.subplots(**{'figsize':[18,6]})
display2.plot('CorDiv', cmap='BrBG_r', vmin=-0.02, vmax=0.02)
ax.set_xlim(tot_range/1000, 0)
plt.show()"

#% Mapping to a Cartesian Grid
print('Mapping Cartesian Grid...\n')
grid = pt.map.grid_from_radar(radar, grid_shape=(20, 700, 700),
""
92
grid_limits=[[0,10000],
[-tot_range,tot_range],
[-tot_range,tot_range]])

# For Counties
os.chdir('C:\Users\Evan\Desktop\Thesis Work')
reader = shpreader.Reader('MO_2018_County_Boundaries.shp')
counties = list(reader.geometries())
for i in range(len(counties)):
    counties[i].crs = ccrs.Geodetic() # For some reason, need to
define the CRS for every county
projection =
crs.LambertConformal(central_latitude=radar.latitude['data'][0],
central_longitude=radar.longitude['data'][0])
COUNTIES = cfeature.ShapelyFeature(counties, ccrs.Geodetic())

# Computing vertical motion
grid_div = grid.fields['CorDiv']['data']
sigma = sum(grid_div[i,:,:] for i in range(10)) # 10 because that is
4500-5000m (roughly the LND)

avg_w = -(sigma*5000)/10 # 5000 because that is top of the grid point
w_max = '{:.2f}'.format(np.amax(avg_w))
w_min = '{:.2f}'.format(np.amin(avg_w))

os.chdir('C:\Users\Evan\Desktop\Thesis Work\Images')

XY = np.linspace(-tot_range, tot_range, num=700)
fig, ax = plt.subplots(subplot_kw={'projection':projection},**{'figsize':[12,10]})
im = ax.pcolormesh(XY, XY, avg_w, cmap='RdBu_r', vmin=-60, vmax=60)
a.add_feature(COUNTIES, facecolor='none', edgecolor='gray')
an.text(75000-54875,75000-7875, 'Max UD = ' + w_max, color='indianred',
horizontalalignment='left', fontsize=14)
an.text(75000-54875,75000-13875, 'Max DD = ' + w_min, color='steelblue',
horizontalalignment='left', fontsize=14)

+ filename[17:19] +
    ':' + filename[19:21] + 'Z

Vertical Velocity')
an.set_extent([-7500,7500, -7500,75000], crs=projection)
ax.gridlines(draw_labels=True, xlocs=[-91,-90], ylocs=[38,39])
plt.colorbar(im, label='VVel (m/s)')
plt.show()

References


