Convective Cores in Continental and Oceanic Thunderstorms: Strength, Width, and Dynamics

THESIS

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Alexander Michael McCarthy, B.S.
Graduate Program in Atmospheric Sciences

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Master's Examination Committee:

Jialin Lin, Advisor
Jay Hobgood
Bryan Mark
Abstract

While aircraft penetration data of oceanic thunderstorms has been collected in several field campaigns between the 1970’s and 1990’s, the continental data they were compared to all stem from penetrations collected from the Thunderstorm Project in 1947. An analysis of an updated dataset where modern instruments allowed for more accurate measurements was used to make comparisons to prior oceanic field campaigns that used similar instrumentation and methodology. Comparisons of diameter and vertical velocity were found to be similar to previous findings. Cloud liquid water content magnitudes were found to be significantly greater over the oceans than over the continents, though the vertical profile of oceanic liquid water content showed a much more marked decrease with height above 4000 m than the continental profile, lending evidence that entrainment has a greater impact on oceanic convection than continental convection.

The difference in buoyancy between vigorous continental and oceanic convection was investigated using a reversible CAPE calculation. It was found that for the strongest thunderstorms over the continents and oceans, oceanic CAPE values tended to be significantly higher than their continental counterparts. Alternatively, an irreversible CAPE calculation was used to investigate the role of entrainment in reducing buoyancy for continental and oceanic convection where it was found that entrainment played a greater role in diluting oceanic buoyancy than continental buoyancy.
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Vita

May, 2011 ........................................Canton Central Catholic High School

May, 2015 ........................................B.S. Atmospheric Science, The Ohio State University

Fields of Study

Major Field: Atmospheric Sciences
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<td>Convective Available Potential Energy</td>
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<td>CaPE</td>
<td>Convection and Precipitation Experiment</td>
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<td>CIN</td>
<td>Convective Inhibition</td>
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<td>COPS</td>
<td>Cooperative Oklahoma Profiler Study</td>
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<td>GARP</td>
<td>Global Atlantic Research Program</td>
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<td>GATE</td>
<td>GARP Atlantic Tropical Experiment</td>
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<td>LCL</td>
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<td>NDTE</td>
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<td>TAMEX</td>
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<td>TOGA COARE</td>
<td>Tropical Ocean Global Atmosphere Coupled Ocean Atmosphere Response Experiment</td>
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<tr>
<td>$w$</td>
<td>Mixing Ratio</td>
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<tr>
<td>$\bar{w}$</td>
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<tr>
<td>$C_p$</td>
<td>Specific Heat Capacity at Constant Pressure</td>
</tr>
<tr>
<td>$C_{pw}$</td>
<td>Specific Heat Capacity at Constant Volume</td>
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<td>Gas Constant</td>
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<td>$e$</td>
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<tr>
<td>$R_w$</td>
<td>Gas Constant for Water Vapor</td>
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<tr>
<td>$L$</td>
<td>Latent Heat of Vaporization</td>
</tr>
<tr>
<td>$S$</td>
<td>Entropy</td>
</tr>
<tr>
<td>$\varepsilon$</td>
<td>A constant equal to 0.622</td>
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<tr>
<td>$T_\rho$</td>
<td>Density Temperature</td>
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Chapter 1: Introduction

During World War II, severe turbulence within thunderstorms was found to be a significant threat to aircraft taking part in the war effort. Because of this, a project for investigating thunderstorm properties was developed and ultimately headed by the Weather Bureau. This “Thunderstorm Project” took place in 1947 and was the first time that comprehensive aircraft penetrations into thunderstorms were utilized to retrieve data. Byers and Braham (1948) were the first to present on the findings of these updraft and downdraft penetrations. They investigated how long these drafts lasted, and found that often they would rise, or fall, for as long as 30 minutes. They attributed the causes of these updrafts to positive buoyancy, air parcels being warmer than the surrounding environment, but noted that the buoyancy was not as great as predicted by parcel theory. They were not, however, able to determine the cause of the downdrafts they encountered. Updrafts had a tendency to be stronger in magnitude and larger in diameter than the downdrafts sampled during the Thunderstorm Project.

A little over a decade later, hurricane updraft and downdraft data acquired from aircraft penetrations was analyzed by Gray (1965). This data was acquired from flights that occurred during the National Hurricane Research Project in 1958 and included penetration data from three storms: Cleo, Daisy, and Helene. He found that the average maximum updraft velocity was 4.01 m/s while the average downdraft velocity was 3.70
m/s. These hurricane updraft velocities were found to be weaker than their continental counterparts, though the downdraft velocities were comparable. Updraft diameters were found to be 1.3 miles whereas downdrafts were found to be 1.5 miles wide. These updraft diameters were comparable with the updrafts analyzed by Byers and Braham (1948), though the downdrafts found by Gray (1965) were nearly 50% larger than those of the Thunderstorm Project.

In 1974, the Global Atmospheric Research Program (GARP) completed the GARP Atlantic Tropical Experiment (GATE) during which some of the earliest aircraft penetrations of oceanic updrafts were acquired. This experiment, which took place off of the western coast of Africa, had the goal of better understanding the structure of tropical convective systems, as well as how they transport mass and heat through the troposphere (Houze and Betts, 1981). When collecting penetration data, airplanes equipped with an inertial navigation system were utilized, which in turn allowed for more accurate calculations of draft and core vertical velocities and diameters.

These updrafts and downdrafts were analyzed by Zipser and Lemone (1980) and Lemone and Zipser (1980) and compared to those updrafts form the Thunderstorm Project as measured by Bryers and Brahm (1949). They found first that the vertical velocities of the drafts and cores measured during GATE were significantly weaker than their counterparts from the Thunderstorm Project. The vertical velocities did compare well to those sampled from hurricanes by Gray (1965). Furthermore, they noted that the GATE drafts and cores were smaller in diameter than those from the Thunderstorm Project, though this was likely a result of the differences in how the drafts were selected.
and measured. If several Thunderstorm Project cores were located in close proximity, they were sometimes grouped together and measured as one single large core rather than several smaller cores.

LeMone and Zipser (1980) went on to discuss the relationships between mass flux, diameter, and vertical velocity of GATE cores. They found that a significant portion of the mass flux was associated with low vertical velocities and small diameters. This led them to come to conclude that weak and narrow updrafts are crucial for the vertical transports within oceanic thunderstorms. When they investigated whether core diameter and vertical velocity were related, they found that the correlations were quite low. LeMone and Zipser (1980) and Zipser and LeMone (1980) also investigated vertical profiles of diameter, vertical velocity, and mass flux, as well as horizontal profiles of mean and maximum vertical velocity. They found that core diameters remain rather constant with height. The vertical velocities of updraft and downdraft cores increase with height in the lowest 3 km and 1.5 km, respectively, before becoming uniform with height. Above this they remain constant. Mass flux tends to maximize near the cloud base before decreasing with height in both updraft and downdraft cores. Using a horizontal profile of vertical velocity, LeMone and Zipser (1980) wanted to determine if the shape of the updrafts were closer to a “top-hat” or “triangle”. In other words, was there a sharp increase in vertical velocity followed by constant vertical velocity before decreasing or was there an increase in vertical velocity to a point maximum before decreasing again. Though a few instances of “top-hat” profiles were found, the vast majority of cores
adhered to the “triangle” profile, which led LeMone and Zipser (1980) to conclude that a linear triangular profile could be used to model vertical velocities.

Although hurricanes were sampled to an extent in GATE, more work needed to be done to determine how the drafts of more intense hurricanes compared to the results from GATE and the Thunderstorm project. Like the measurements utilized in the Thunderstorm Project, the measurements Gray (1965) used were collected from an airplane that lacked Internal Navigation Equipment, and therefore newer penetration data was collected using airplanes that contained such equipment. Jorgensen et al. (1985) targeted mature hurricanes in their study, and found that the vertical motions of such hurricanes were similar in magnitude to those found by LeMone and Zipser (1980) as well as Gray (1965). As a consequence of this, they were also much weaker than those observed by Byers and Braham (1949) during the Thunderstorm Project. Interestingly, the diameters of the hurricane drafts, as well as their mass flux, were much larger than those observed in GATE (Jorgensen et al. 1985). Such results were supported by the work of Black et al. (1996) who used radar to analyze several Atlantic hurricanes. Related studies including Case and Garrish (1988), Ebert and Holland (1992), Eastin et al (2004a and b), and Black et al. (1994) found even stronger vertical velocities embedded within hurricanes, with Black et al. (1996) noting that some hurricane rain bands had supercells embedded within them.

The next major field campaign from which oceanic thunderstorm penetration data was acquired occurred in 1987 during the Taiwan Area Mesoscale Experiment (TAMEX), which focused on those storms impacting the subtropical Pacific around
Taiwan, providing data from the Pacific basin which could be compared with that from the Atlantic Basin collected during GATE. The data was analyzed by Jorgensen and LeMone (1989) and they found that these drafts were similar in diameter, vertical velocity, and mass transport to the cores measured from hurricanes (Jorgensen et al. 1985) and in GATE (Zipser and LeMone 1980). In a similar way, TAMEX vertical velocities are weaker than those found in the Thunderstorm project, and much weaker than those observed in later continental field experiments (Musil et al. 1986 for instance). Jorgensen and LeMone (1989) found that the vertical profiles of diameter, vertical velocity, and mass flux were similar to those of GATE. The largest mean vertical velocities occurred slightly lower in TAMEX than in GATE, and the largest magnitudes of mass flux were found to occur slightly higher in TAMEX than GATE, which was just above the TAMEX cloud base. An additional vertical profile was constructed by Jorgensen and LeMone (1989) to show the vertical distribution of cloud liquid water content. They found that cloud liquid water content generally increases in height above the surface but decreases sharply above the freezing level. Such a rapid decrease of liquid water content above the freezing level was not observed with continental liquid water content profiles (Szoke et al. 1986).

In 1987, EMEX took place within the Western Pacific Warm Pool to the north of Australia. Lucas et al. (1994) analyzed the updraft and downdraft cores and found, unsurprisingly, that the cores sampled in EMEX very similar to those of GATE and TAMEX in terms of diameter, vertical velocity, mass flux, and their vertical profiles. Furthermore, they were considerably weaker than those from the Thunderstorm Project.
(Lucas et al. 1994). The fact that EMEX cores were so similar to GATE, TAMEX, and hurricane cores was surprising to them because sea surface temperatures over the Western Pacific Warm Pool are warmer than other oceanic cases. TOGA COARE, which also took place in the Western Pacific Warm Pool, yielded similar results (Igau et al. 1998).

One important question involving data acquisition was whether the definition of a core actually filtered out what would have been more intense cores in the sample. Because the core was defined as having a minimum diameter of 500 m, could it be possible that stronger cores with smaller diameters exist, or that aircraft do not cross a stronger updraft core through its center, and therefore it is filtered out? LeMone et al. (1994) investigated this and found that the effects were evident but not nearly as large as they were thought to be. In particular, some diameters were most likely somewhat smaller than reported, and velocities were diluted some, but the fact still remains that the updraft velocities remained slower than their continental counterparts. Interestingly, the values of mass flux were impacted very little, though the values of mass flux were probably barely smaller than reported.

It should be noted that the GATE, TAMEX, EMEX, and TOGA COARE field experiments all collected penetration data of oceanic drafts, but few continental field campaigns since the Thunderstorm Project has been conducted to yield a large enough sample size of continental updraft and downdraft cores to make statistical comparisons. As discussed by Lucas et al. (1994), this has implications on comparisons of continental and oceanic drafts due to the different sampling methodology of the Thunderstorm
Project in which isolated convective storms were penetrated instead of convection within a mesoscale convective system, as well as the fact that the airplanes from the Thunderstorm Project were not equipped with inertial navigation systems. This is not to say, however, that no further aircraft penetrations of continental updrafts and downdrafts have been taken. Heymsfield et al. (1978) used aircraft penetration data from Colorado cumulus congestus clouds and found vertical velocities as great as 23 m/s. Heymsfield and Smith (1986) analyzed data from a T28 aircraft that penetrated the weak echo region of a Montana supercell thunderstorm. They noted vertical velocities in downdraft cores as high as 15 m/s and in updraft cores as high as 50 m/s, much higher than any vertical velocities measured over the oceans.

The Large Scale Biosphere-Atmosphere (LBA) experiment did penetrate enough updraft cores to provide for meaningful statistics (Anderson et al. 2005). This campaign took place over the Amazon River and sampled continental tropical thunderstorm cores. It was found that these cores were very similar to ones sampled over the tropical oceans, and no comparisons were made with the Thunderstorm Project. Though it is nice to have a sizeable dataset like this, the LBA experiment did not investigate subtropical continental storms or those continental storms over the interior which were measured during the Thunderstorm Project and which need updated measurements. Though these aircraft penetrations are both important and useful, more penetrations of continental thunderstorms are required in order to gather a meaningful collection of in situ data for analysis and comparison with the oceanic field campaigns.
Unlike aircraft penetrations, remote sensing has been useful in gathering large datasets of continental updraft and downdraft cores. Using wind profilers, for instance, Giangrandre et al (2013) investigated updraft and downdraft core properties, though they used a higher vertical velocity threshold of 1.5 m/s compared to 1.0 m/s which was defined by Zipser and LeMone (1980). Using a wind profiler was found to be convenient because it could sample many more updraft and downdraft cores than an aircraft typically would. They found that these updraft and downdraft cores achieved greater vertical velocities than those sampled over the oceans. They also found that updrafts had a tendency to be stronger than downdrafts. Vertical profiles were also obtained for updraft diameters, vertical velocities, and mass flux. Updraft diameter stays relatively constant with height, though increases slightly. Mass flux behaves similarly. Vertical velocity increases with height throughout the lowest 12 km of the atmosphere. These were very similar to their oceanic counterparts, though the increase in velocity over Oklahoma was more pronounced, and the values over Oklahoma of all three of these variables were greater in magnitude than those observed during various oceanic field campaigns.

Likewise, remote sensing has proven useful in better visualizing properties of oceanic cores, especially when it comes to vertical profiles of radar reflectivity. Williams et al. (1992) found that the radar reflectivity of the mixed-phase region was much less over the oceans than over the continents, which they attributed to most of the oceanic precipitation forming and falling below the freezing level. This was investigated more by Zipser and Lutz (1994) who noted that vertical profiles of radar reflectivity taper off above the freezing level in both continental and oceanic thunderstorms, however this
process is gradual over the continents and very rapid over the oceans. They attribute this to a lack of large ice particles above the freezing level over the oceans. This supported earlier work by Szoke et al. (1986) who had noted similar profiles of reflectivity from GATE radar data, and who also showed that hurricanes exhibit similar profiles. More recent work by Heymsfield et al. (2010) also supported these profiles, finding that reflectivity over the oceans is typically 5 dBZ or less than continental reflectivities. Interestingly, they also noted a bimodal profile of vertical velocity over the ocean with peaks around 6 km and 10 km. Fierro et al. (2009) addressed vertical velocity maxima aloft and found that increased buoyancy is likely due to the release of latent heat of freezing.

From the assortment of available in situ and remote measurements of oceanic and continental cores, it is clear that there is a significant difference between them. Why is this so? LeMone and Zipser (1980) were the first to attempt to address this question, and attributed the differences to the sounding environment. The calculated convective available potential energy (CAPE) of GATE and Thunderstorm Project environments based on a representative sounding of each and found that the values of CAPE for each of those environments were 1500 J/kg and 3000 J/kg respectively. From those values, they calculated the expected updraft velocities using the equation

\[ w = \sqrt{2 \cdot CAPE} \]  

(Equation 1)

and found that Thunderstorm Project updrafts achieved a greater proportion of their potential vertical velocity, as predicted by parcel theory, than the GATE updrafts did. This finding led to two additional questions that needed answers: (1) is CAPE alone
responsible for limiting vertical velocities of oceanic convection; and (2) why does oceanic convection reach a smaller proportion of its total potential vertical velocity, as predicted by parcel theory? The answer to the first question was addressed first by Griffith (1992), who identified that EMEX soundings had values of CAPE that were very similar to those found in the Thunderstorm Project. Lucas et al. (1994b) followed up with a correction to the work of Zipser and LeMone (1980), noting that the value of Thunderstorm Project CAPE which they had calculated was only around 1950 J/kg, much smaller than the 3000 J/kg which they had originally calculated. With this new representative continental CAPE value, Lucas et al. (1994b) claimed that “there is now no basis at all for attributing the difference to differences in CAPE over land and water.” Lucas et al. (1994a) did, however, include a discussion on the differences in the aspect ratios between continental and oceanic soundings. They noted that although values of CAPE were similar over the continents and the oceans, the shapes of the soundings were different in that continental soundings tended to be shorter and fatter whereas oceanic soundings had a tendency to be taller and thinner. In other words, virtual temperature excesses tend to be much larger in continental convection than in oceanic convection. Though this alone cannot fully explain the differences in velocities of continental and oceanic updraft cores, it does impact the dynamic and thermodynamic processes that can dilute oceanic updrafts more so than their continental counterparts.

Further research into this matter determined that continental updraft cores had a tendency to be much less diluted than their oceanic counterparts. Davies-Jones (1974) analyzed four different soundings and found that their associated updrafts tended not to
be diluted in the mid-levels of the atmosphere. In a more comprehensive review, Zipser (2003) pointed out that undilute updrafts are common over the continents but extremely rare over the oceans.

The second question of why oceanic updrafts achieve a smaller fraction of their maximum predicted vertical velocity still remains to be answered. Lucas et al. (1994b) suggests that water loading, entrainment, and less buoyancy in the lower levels could be responsible for this. Lucas et al. (1994a) discuss the role of water loading in more detail by pointing out that “fatter” soundings would be less influenced by water loading than skinny soundings. If a continental and oceanic sounding had the same magnitude of CAPE, yet stereotypical aspect ratios, then it would be expected that the oceanic updrafts would be impacted more by water loading than their continental counterparts. Because water loading leads to negative buoyancy of the updrafts, this would lead to lower vertical velocities for oceanic convection than continental convection for a given value of CAPE. Lucas et al. (1994a) points out that a comprehensive sounding analysis must be performed to determine the validity of this hypothesis.

Lucas et al. (1994b) also discuss the possibility that oceanic updraft cores are more susceptible to entrainment than continental cores. The relationship between entrainment and buoyancy was noted by Telford (1975), and therefore it is reasonable to suspect that the reason why virtual temperature deviations in oceanic updrafts do not reach their expected adiabatic values may be due to the role of entrainment in reducing buoyancy. According to Stommel (1947), during entrainment, dry environmental air is brought into the updraft and mixes with the moist air parcels within the updraft, thereby
reducing their buoyancy. As a result, as described by Byers and Braham (1948), entrainment results in the lapse rate becoming steeper than the adiabatic lapse rate, and therefore the positive CAPE area is reduced.

Lucas et al. (1994) point out that continental updraft cores tend to be greater in diameter than oceanic updraft cores. It has been shown by McCarthy (1974) that there is a positive relationship between updraft core diameter and entrainment rate, though work by Heymsfield (1979) pointed out that these conclusions may have been based on incomplete data due to the restrictions of the Rosemont sensor that McCarthy had used. Lucas et al. (1994b) go on to point out that although differences in diameters between continental and oceanic updrafts are speculative, based on Thunderstorm Project data collected by rather primitive methods, boundary layer depths that have been observed over the continents and oceans support this difference in diameter.

Lastly, Lucas et al. (1994b) support this entrainment argument by discussing virtual temperature excesses located around the freezing level. Their findings indicate that vertical temperature excesses are “substantially” less than what they expected from parcel theory. They attribute this to low level entrainment, but point out that entrainment is difficult to quantify for a variety of reasons. The updrafts may reside in an environment completely different than that modeled by the sounding, they may originate at different levels with different initial conditions, and there are uncertainties in the height at which the entrained air originates. Detailed information regarding entrainment models and processes can be found in Blyth’s (1993) review, Reuter’s (1986) review, and Houze (2014). Early concepts of entrainment, such as that proposed by Squires (1958), included
the idea that downdrafts diluted the updraft from the top down. Decades later, Knupp and Cotton (1985) found evidence of penetrative updrafts, which confirmed Squires’ (1958) idea of vertical, rather than horizontal, entrainment. Though a lateral entrainment model was proposed, it was found by Warner (1970) that they do not accurately predict cloud depth and water content at the same time. These results were supported by the work of Raymond and Wilkening (1982).

Michaud 1996 replied to the report of Lucas et al. (1994b), supporting the idea that entrainment could account for oceanic updraft cores achieving a smaller fraction of their total vertical velocity by stressing the importance of evaporative cooling. He goes on to point out that rising parcels can actually grow from entrainment up to the lifted condensation level due to evaporative cooling above the LCL will reduce their size. Because the LCL is higher over the continents, it would allow for the updrafts to grow to larger diameters before evaporative cooling would be a factor, whereas oceanic updrafts would lose buoyancy quickly due to evaporative cooling.

Lucas et al. (1996) replied to the evaporative cooling argument by pointing out that most of the updrafts sampled by oceanic field campaigns occurred in disturbed environments, that is they occurred in environments that were impacted by a mesoscale convective system. This means that entrained air would be nearly saturated and would reduce the role of evaporative cooling in reducing buoyancy in oceanic convection. Furthermore, they suggest that the lack of surface humidity over the continents would weaken, not strengthen continental updrafts. Though they agree that the depth of the boundary layer is important in explaining why oceanic updrafts become more dilute, they
bring up a hypothesis that convective inhibition (CIN) is important. They reference that magnitudes of CIN tend to be higher over the continents than over the oceans. When values of CIN are high, parcels below the LCL must be accelerated by some form of dynamic forcing, leading to laminar ascent which would limit the amount of entrainment that would occur until the parcel surpasses the level of free convection. Lucas et al. (1996) points out that this would yield similar results to Michaud’s hypothesis, but it better explains why oceanic updrafts are diluted more by entrainment.

Michaud (1998) investigates the impact of relative humidity at various levels of the atmosphere on updraft virtual temperature excesses. He found that virtual temperature excesses are more sensitive to lower relative humidities aloft, and that if the relative humidity aloft becomes less than 50%, the updraft may completely loose its buoyancy. These results are also supported by the work of Raymond (1995) who notes that there can be a lack of deep convection, even when CAPE values are significant, if there is dry air aloft. He goes on to attribute higher LCL values over the continents to lower surface humidity, which would allow for continental updraft cores to be able to avoid the effects of evaporative cooling due to entraining of environmental air for a greater depth.

Wei et al. (1998) investigated the buoyancy of TOGA COARE thunderstorms and found that entrainment played a larger role in reducing updrafts buoyancy than did water loading. In fact, they went on to make the claim that water loading in some cases may reduce buoyancy, but this is only a temporary effect compared to entrainment. Xu and Randall (2001) make use of cloud resolving models in order to analyze the statistics of updraft and downdraft properties as functions of height, from which they
concluded that differences in buoyancy and water loading had a greater impact on
diluting the buoyancy of oceanic updrafts compared to downdrafts.

The data gathered from oceanic field campaigns paint a picture of stronger
continental midlatitude updrafts than oceanic updrafts, however, it has been pointed out
by Zipser and LeMone (1980) that there are important differences between how
Thunderstorm Project updrafts and downdrafts were sampled compared to those of
GATE and the rest of the oceanic field campaigns that would follow GATE.
Furthermore, as pointed out by Xu and Randall (2001), no further field campaign has
produced a representative sample of continental updrafts and downdrafts from which
meaningful statistics could be obtained. There also has been much debate as to what
causes updrafts to be slower over the oceans than the continents, and ultimately new data
from the continents must be included if this debate is to be brought back into the spotlight
and ultimately settled. Therefore, there are four main goals of this thesis:

1) A new dataset of continental aircraft penetration data that is representative of
convection found in the midlatitudes from three separate regions will be analyzed,
from which meaningful updraft and downdraft core statistics will be obtained.

2) The values of liquid water content from oceanic and continental thunderstorms
will be analyzed to determine what differences exist and whether they are
significant. This will provide in-situ evidence of how important the role of
entrainment is in diluting the buoyancy of oceanic and continental updraft cores.

3) Properties of continental and oceanic soundings associated with vigorous updrafts
will be analyzed using a reversible CAPE calculation that takes into consideration
the effects of the freezing process and the related release of latent energy. This will allow for an analysis of how values of CAPE, CIN, LCL pressure levels, LNB pressure levels, and density temperature deviations compare when entrainment is not occurring.

4) Properties of continental and oceanic soundings associated with vigorous updrafts will again be analyzed using a CAPE calculation that takes into consideration the effects of lateral entrainment and cloud top entrainment to see how they influence overall CAPE values. This will allow for an analysis on whether entrainment has a greater impact on continental or oceanic convection.
Chapter 2: Datasets Gathered for Analysis

In order to perform the research that was the goal of this thesis, both aircraft and sounding data were required. Figure 1 below illustrates the locations of the field campaigns from which the aircraft penetration data was acquired, as well as the stations from which the soundings were obtained.

![Aircraft Penetration Data and Sounding Locations](image)

Figure 1. Locations of field campaigns used in this thesis

For the first part of this thesis, aircraft penetration data from the continents and oceans are analyzed in order to examine updraft and downdraft core properties. Over the
continents, a dataset of continental penetration data is created using data found on the NCAR UCAR Earth Observing Laboratory website. This data was collected from several field campaigns including the North Dakota Tracer Experiment (NDTE), which collected data over the Dakotas, the Convection and Precipitation/Electrification Experiment (CaPE) over east-central Florida, and the Cooperative Oklahoma Profiler Study (COPS), Vortex 1994, and Vortex 1995 over central Oklahoma. This dataset consisted of 24 unique aircraft flights on thunderstorm days during which 877 unique updraft and 2071 downdraft penetrations took place, allowing for comparisons with oceanic field data that could be checked for statistical significance. Information on exact flights, including flight numbers, dates, and times can be found in Tables 1-5 below:
<table>
<thead>
<tr>
<th>Flight Number</th>
<th>Date</th>
<th>Time (UCT)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Flight 609</td>
<td>7/16/1993</td>
<td>00:08-01:49</td>
</tr>
<tr>
<td>Flight 611</td>
<td>7/22/1993</td>
<td>17:02-18:30</td>
</tr>
<tr>
<td>Flight 612</td>
<td>7/23/1993</td>
<td>22:50-00:28</td>
</tr>
</tbody>
</table>

Table 1. Dates and times of flights from the North Dakota Tracer Experiment
<table>
<thead>
<tr>
<th>Flight Number</th>
<th>Date</th>
<th>Time (UCT)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Flight 558</td>
<td>7/12/1991</td>
<td>17:55-20:26</td>
</tr>
<tr>
<td>Flight 559</td>
<td>7/14/1991</td>
<td>20:46-23:09</td>
</tr>
<tr>
<td>Flight 571</td>
<td>8/08/1991</td>
<td>16:42-18:54</td>
</tr>
</tbody>
</table>

Table 2. Flight dates and times from the Convection and Precipitation Electrification Experiment

<table>
<thead>
<tr>
<th>Flight Number</th>
<th>Date</th>
<th>Time (UCT)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Flight 541</td>
<td>5/19/1991</td>
<td>16:10 - 18:00</td>
</tr>
<tr>
<td>Flight 544</td>
<td>5/30/1991</td>
<td>18:10 - 20:30</td>
</tr>
<tr>
<td>Flight 545</td>
<td>6/01/1991</td>
<td>15:40 - 18:00</td>
</tr>
<tr>
<td>Flight 547</td>
<td>6/05/1991</td>
<td>11:30 - 13:45</td>
</tr>
</tbody>
</table>

Table 3. Flight dates and times from the Cooperative Oklahoma Profiler Study
<table>
<thead>
<tr>
<th>Flight Number</th>
<th>Date</th>
<th>Time (UCT)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Flight 624</td>
<td>5/25/1994</td>
<td>23:00-00:43</td>
</tr>
</tbody>
</table>

Table 4. Flight dates and times from the Vortex 1994 Field Experiment

<table>
<thead>
<tr>
<th>Flight Number</th>
<th>Date</th>
<th>Time (UCT)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Flight 655</td>
<td>5/05/1995</td>
<td>20:34-22:21</td>
</tr>
<tr>
<td>Flight 656</td>
<td>5/07/1995</td>
<td>16:00-17:41</td>
</tr>
</tbody>
</table>

Table 5. Flight dates and times from the Vortex 1995 Field Experiment

Over the oceans, data was collected over the Western Pacific Warm Pool using data collected during TOGA COARE by both two NOAA WP-3Ds as well as one Electra aircraft. For this, information from 25 aircraft flights on thunderstorm days was analyzed, allowing for 1677 updrafts and 1055 downdrafts to be sampled. This again allows for statistical comparisons to be made with the aforementioned continental data. More information on these flights can be found in Yutter et al. (1995). It should be noted that unlike the Thunderstorm Project where isolated thunderstorms were intercepted, a wide variety of different convective events were sampled here, and most penetrations occurred in a disturbed environment.
During each of these field campaigns, several variables were observed by these aircraft which constantly measured both dynamic and thermodynamic properties along the flight legs. Measurements of vertical velocity and cloud liquid water content were of special importance since they were analyzed in this thesis. Vertical velocity was measured using a method defined by Kopp (1985) and requires three variables; pitch angle, static pressure, and dynamic pressure. This pitch angle is measured by the Humphrey SA09-D0101-1 Vertically Stabilized Accelerometer, the static pressure is measured by the Rosemount 1301-A-4B sensor, and dynamic pressure is measured by the Rosemount 1301-D-1b sensor. Cloud liquid water content was measured by a Johnson Williams meter, which is described in more detail by Merceret and Schricker (1975).

In order to compare different thermodynamic values that are derived from atmospheric soundings, ample soundings needed to be gathered from the continents and oceans to establish statistical significance in any differences that may be found. The goal is to find those soundings that are associated with convection that would be conducive to strong updrafts, which manifest themselves by creating conditions favorable for lightning. Though records of lightning are sparse, especially over the western Pacific, rainfall records are easier to come by. Studies on lightning flash rates and precipitation, such as Parczewski (1958), Kinzer (1974), and Nielsen et al. (1990) indicate that there is a good correlation between rainfall rate and lightning frequency. This would lead to the idea that storms exhibiting heavy rainfall are most likely to exhibit lightning, and therefore strong convective updrafts.
Using the archives of the National Oceanic and Atmospheric Administration’s (NOAA) National Centers for Environmental Information (NCEI), hourly precipitation records were obtained from sites in the Western Pacific Warm Pool and the continental United States between the years 2000 and 2013. Specific locations used can be found in Table 06 and Table 07 below:

<table>
<thead>
<tr>
<th>Station Name</th>
<th>State</th>
<th>Sounding</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bainbridge International</td>
<td>GA</td>
<td>TLH</td>
</tr>
<tr>
<td>Dowling Park</td>
<td>FL</td>
<td>TLH</td>
</tr>
<tr>
<td>Monticello</td>
<td>FL</td>
<td>TLH</td>
</tr>
<tr>
<td>Tallahassee</td>
<td>FL</td>
<td>TLH</td>
</tr>
<tr>
<td>Chandler</td>
<td>OK</td>
<td>OUN</td>
</tr>
<tr>
<td>Chickasha</td>
<td>OK</td>
<td>OUN</td>
</tr>
<tr>
<td>Custer</td>
<td>OK</td>
<td>OUN</td>
</tr>
<tr>
<td>Fort Cobb</td>
<td>OK</td>
<td>OUN</td>
</tr>
<tr>
<td>Geary</td>
<td>OK</td>
<td>OUN</td>
</tr>
<tr>
<td>Guthrie</td>
<td>OK</td>
<td>OUN</td>
</tr>
</tbody>
</table>

Continued

Table 6. Sites of acquisition of continental precipitation data and soundings
Table 6 continued

<table>
<thead>
<tr>
<th>Location</th>
<th>Abbreviation</th>
<th>Type</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lake Overholser</td>
<td>OK</td>
<td>OUN</td>
</tr>
<tr>
<td>Okarche</td>
<td>OK</td>
<td>OUN</td>
</tr>
<tr>
<td>Okemah</td>
<td>OK</td>
<td>OUN</td>
</tr>
<tr>
<td>Will Rogers Airport</td>
<td>OK</td>
<td>OUN</td>
</tr>
<tr>
<td>Paoli</td>
<td>OK</td>
<td>OUN</td>
</tr>
<tr>
<td>Wole</td>
<td>OK</td>
<td>OUN</td>
</tr>
<tr>
<td>Wolf</td>
<td>OK</td>
<td>OUN</td>
</tr>
<tr>
<td>Cottonwood</td>
<td>SD</td>
<td>RAP</td>
</tr>
<tr>
<td>Edgemont</td>
<td>SD</td>
<td>RAP</td>
</tr>
<tr>
<td>Harrison</td>
<td>SD</td>
<td>RAP</td>
</tr>
<tr>
<td>Interior 3</td>
<td>SD</td>
<td>RAP</td>
</tr>
<tr>
<td>Mule Creek</td>
<td>WY</td>
<td>RAP</td>
</tr>
<tr>
<td>Newcastle</td>
<td>WY</td>
<td>RAP</td>
</tr>
<tr>
<td>Osage</td>
<td>WY</td>
<td>RAP</td>
</tr>
<tr>
<td>Pactola Dam</td>
<td>SD</td>
<td>RAP</td>
</tr>
<tr>
<td>Plainview</td>
<td>SD</td>
<td>RAP</td>
</tr>
<tr>
<td>Rapid City</td>
<td>SD</td>
<td>RAP</td>
</tr>
</tbody>
</table>
A group of occurrences of heavy hourly precipitation, defined as 0.3 inches (7.62 mm) by the American Meteorological Society, was created and a simple random sample of 100 occurrences over the continental United States and 100 occurrences from the western pacific warm pool was obtained. The dates and times of these occurrences were analyzed, and those occurrences that took place between November and February were neglected from the dataset in order to eliminate winter weather events from the dataset. Using the dates and times associated with each entry of this dataset, sounding data was obtained from the archives of the University of Wyoming’s Department of Atmospheric Science. A dataset consisting of a simple random sample of 100 continental soundings and 100 oceanic soundings was compiled so that a statistical analysis could be performed.
Chapter 3: Methodology

Once the aircraft data was obtained, updraft and downdraft cores needed to be found in order to complete the analysis. To accurately represent the properties of updraft and downdraft cores, portions of the flight legs occurring while the aircraft was turning or changing altitude needed to be selected. In order to isolate such straight horizontal flight legs, time series plots of altitude, latitude, and longitude were examined in the following process:

1) Horizontal flight legs were chosen

2) For each horizontal flight leg, measurements of latitude were analyzed to filter out those portions where changes of latitude were constant

3) For each horizontal flight leg in which changes in latitude were constant, the longitude was analyzed and those segments of the flight legs where changes in longitude was constant were kept

4) The corresponding time series of vertical velocity of these segments of flight legs was saved

Once time series data of vertical velocity from straight level flight legs was obtained in, updraft and downdraft cores were selected for analysis using a program written by this author in IDL. This program can be found in appendix A. In this program, the cores were
defined analogously to the definitions of Zipser and LeMone (1980) such that they have a 
vertical velocity of at least 1.0 m/s for at least 500m and downdrafts have a vertical 
velocity of at least 0.5 m/s for at least 500 m. For downdraft vertical velocity, the positive 
direction has been arbitrarily defined so that it is orientated towards the surface of the 
Earth. In order to calculate the diameter of updraft and downdraft cores, IDL’s 
“MAP_2POINTS” function was used. The latitude and longitude coordinates of the first 
and last data point in the updraft and downdraft cores were read by the function and a 
distance, specified here to be in units of meters, was returned for each updraft. Further 
filtering was performed to remove all cores with a diameter less than 500 m to 
accommodate the definitions specified by Zipser and LeMone (1980). Along with the 
diameters of these updraft and downdraft cores, this code also included calculations to 
find the maximum vertical velocity and averages of vertical velocity and liquid water 
content for each core.

Likewise, this author wrote a program to calculate CAPE for each of the gathered 
soundings. This calculation was also modified to incorporate the impact that various 
entrainment rates would have on reducing those CAPE values. This program was written 
in a manner similar to the one defined by Randall and Wang (1992). The thermodynamic 
equations used were obtained from Lorenz (1979). The initial entropy is calculated using 
the equation

\[(1 + \bar{w})s = (C_p + \bar{w}C_{pw}) \ln T - R \ln (p - e) - \bar{w}R_w \ln e - (\bar{w} - w) \frac{L}{T} \]  
(Equation 2)
using the initial values of temperature, pressure, and mixing ratio for this calculation. Because the parcel’s entropy is conserved, as the parcel rises, it’s new temperature can be calculated by an iterative method using the equation

\[ \Delta T = \frac{s - \hat{s}}{\left(\frac{\partial s}{\partial T}\right)_p} \]  

(Equation 3)

The temperature was then converted to density temperature using the equation

\[ T_\rho \equiv T \frac{1 + \frac{r}{\epsilon}}{1 + \frac{r}{T}} \]  

(Equation 4)

from Emanuel (1994). Unlike other CAPE calculations, including that of Randall and Wang (1992), that use virtual temperature, this CAPE calculation used density temperature out of convenience, for the equation to calculate CAPE, as derived by Emanuel (1994), is quite straightforward when using density temperature:

\[ CAPE_i = NA_i - PA_i \]  

(Equation 5)

Where

\[ NA_i = - \int_{P_{sfc}}^{P_{lcl}} R_d \left(T_{\rho_{par}} - T_{\rho_{env}}\right) d \ln P \]  

(Equation 6)

\[ PA_i = \int_{P_{lcl}}^{P_{lnb}} R_d \left(T_{\rho_{par}} - T_{\rho_{env}}\right) d \ln P \]  

(Equation 7)

This computation method is preferred because it is reversible and incorporates the effects of ice phase thermodynamics, which many other CAPE calculation methods do not.

Mixing was also incorporated into this calculation to identify the role that entrainment plays in diluting soundings. The method dictates that entropy and mixing ratio of the air parcel at a given level was diluted to a mixture of a certain percentage of environmental air and parcel air. The basic equations are:
\[ S_{new} = S_{par} \cdot (1 - x) + S_{env}(x) \] (Equation 8)
\[ W_{new} = W_{par} \cdot (1 - x) + W_{env}(x) \] (Equation 9)

Here, \( x \) represents the percentage of environmental air that is in the mixture.

Three different mixtures were calculated. The first two assumed lateral entrainment and used a mixture of 1% environmental air and 99% parcel air, and 10% environmental air and 90% parcel air respectively. The third mixture assumed cloud-top entrainment and assumed a mixture of 20% environmental air and 80% parcel air above the 400 mb level and 1% environmental air and 99% parcel air below the 400 mb level.

Most of the attempts to explain differences in continental and oceanic soundings thus far have made the assumption that rising air parcels originate at the surface, below the LCL. It turns out, however, that elevated convection over the continents is not particularly uncommon and can produce vigorous updrafts with limited values of surface-based CAPE. Because of this, a second CAPE calculation was created to calculate the most unstable CAPE (MUCAPE) of the soundings. This ended up being a modified version of the aforementioned CAPE calculation based on the calcsound developed by Kerry Emanuel. In the lowest third of the atmosphere, CAPE was calculated at each level in the sounding following a parcel that was assumed to originate at each level. Continental and oceanic soundings that exhibited less than 1000 J/kg of CAPE were retested and checked to see if there were larger values of CAPE found if the parcel had originated at a higher level. If it was indeed found that this was the case, they were removed from this dataset in order for only surface based CAPE to be analyzed.
Chapter 4: Analysis of Aircraft Penetration Data

Although oceanic thunderstorm penetration data has been gathered and analyzed in multiple studies, continental thunderstorm penetration data is harder to acquire. Indeed, very useful data was gathered from the Thunderstorm Project by Byers and Braham (1948), however the instrumentation used to take dynamic and thermodynamic measurements of the updrafts and downdrafts was primitive compared to the instrumentation utilized during most of the oceanic studies. Therefore, though comparisons could be made between Thunderstorm Project drafts and cores and those from oceanic studies, there is room for error, especially since instruments used for oceanic field campaigns from the 1970’s and later were much more refined. In this chapter, continental data from five different field campaigns over the continental United States, where similar sampling methodologies were used, is analyzed and compared with both the Thunderstorm Project and various oceanic campaigns. Unlike the continental dataset collected during the Thunderstorm Project, the dataset gathered for this thesis utilized an inertial navigation system, and followed the definitions of updraft and downdraft cores that have been adopted by the various oceanic field campaigns.
From the aircraft penetration data set that was compiled and analyzed in this thesis, there were 877 updrafts recorded. Following the methodology of Zipser and LeMone (1980), those updrafts with diameters of at least 500 meters were selected for analysis, which totaled 410 unique updrafts. The average diameter for the continental cases was 1611.31 meters. Because updraft penetrations occurred at three distinct regions over the continental United States, the diameters were separated based on their location and it was found that the population mean diameters for South Dakota, Oklahoma, and Florida updrafts were 1775.15 meters, 1419.72 meters, and 1682.92 meters respectively, and are displayed graphically in Figure 2 below:

![Continental Updraft Diameters](image)

**Figure 2.** Continental updraft diameters from Florida, Oklahoma, and South Dakota thunderstorm penetrations
In order to determine whether or not there was significant variance between observations from South Dakota, Oklahoma, and Florida, various analyses of variance (ANOVA) tests are conducted throughout this thesis. With all of these, the null hypothesis is always that the population means of the variable sampled at each of the three locations are the same. The alternative hypothesis is that at least one of those means is different. If the ANOVA produces evidence to suggest that the alternative hypothesis is correct, than T-tests are conducted to determine which population is different.

Here, an ANOVA test is conducted to determine if any of these mean diameters were significantly different from the rest. Using a one-way ANOVA with a confidence level of 95%, a p-value of 0.15 was obtained, providing evidence that there is no statistically significant difference between the population mean diameters at the three specified locations.

The average mean vertical velocity of continental updrafts was also analyzed both in terms of the mean updraft velocity and maximum updraft velocity. The mean vertical velocity of the entire sample of continental updrafts was found to be 3.25 m/s. Again these vertical velocities were divided into three separate groups based on their location of acquisition and it was found that the mean updraft velocities for South Dakota, Oklahoma, and Florida were 3.20 m/s, 2.89 m/s, and 3.73 m/s. These are displayed in Figure 3 below:
Again, an analysis of variance was conducted using a one-way ANOVA with a confidence level of 95%. A p-value of 0.002 was calculated indicating that there was evidence to suggest that the population means of at least one of the regions was significantly different from the rest. Using two-sample t-tests where population variance was assumed to be unknown, it was determined that the population mean updraft velocity for the Florida updrafts differed significantly from those in Oklahoma and South Dakota.

The average maximum updraft velocity for the continental updrafts was found to be 5.14 m/s. When divided by region of acquisition, the average maximum updraft
velocities were found to be 5.19 m/s, 4.43 m/s, and 5.93 m/s for South Dakota, Oklahoma, and Florida respectively, graphically displayed in Figure 4 below:

Figure 4. Continental updraft maximum vertical velocity from Florida, Oklahoma, and South Dakota thunderstorm penetrations

Again, a one-way ANOVA with a 95% confidence level was utilized to see if there was any significant variation in maximum vertical velocity between these regions. The p-value of 0.003 indicated that there was ample evidence that the average maximum vertical velocity corresponding to at least one of these locations differed significantly from the others. Two sample t-tests where population variance was assumed to be unknown were utilized again to isolate the different region and it was found that the
maximum vertical velocities observed in Oklahoma were significantly less than those found over Florida and South Dakota.

The average liquid water content measured from continental updrafts was found to be 0.267 g/m³ with values of 0.294 g/m³, 0.114 g/m³, and 0.390 g/m³ measured over South Dakota, Oklahoma, and Florida respectively. These results are displayed in Figure 5 below:

![Figure 5. Continental updraft liquid water content from Florida, Oklahoma, and South Dakota thunderstorm penetrations](image)

Again, due to the variation in means here, a one-way ANOVA with a 95% confidence level was conducted to check to see if there were any differences between the population
means. A p-value of 0.00 indicated that there was indeed evidence to suggest that at least one of the means differed from the other two, and it was found that the mean liquid water content of the updrafts measured over Oklahoma was significantly less from the updrafts over Florida and South Dakota.

Next, the vertical profiles of diameter, velocity, and liquid water content will be discussed. Unlike other field campaigns which penetrated updraft cores at a wide range of altitudes ranging from 200 m above the ground to nearly 7000 m above the ground, the altitude range of this data set was much shallower, ranging from 2500 m to 6000 m. Though this does limits the range of the vertical profiles to a decent distance above the surface, it does allow for a greater vertical resolution within those altitude ranges which is important since such resolution has been weak in prior studies. Because of the abundance of data within this altitude range, the data was separated into 7 different levels with approximately 50 entries in each level so that calculations at each of those levels were significant.

The vertical profile of diameter with respect to altitude can be found above in Figure 6:
The diameters appear to increase with altitude over the first 800 m before decreasing quickly with height between 3800 m and 4200 m. Above this point, the diameters continue to increase with height up to the top of this profile at 6100 m. Figure 7 and Figure 8 show profiles of mean vertical velocity and maximum vertical velocity.
Figure 7. Vertical profile of continental updraft core mean vertical velocity

Figure 8. Vertical profile of continental updraft core maximum vertical velocity
Both of these profiles are similar, showing a marked increase in velocity with height over all levels. Interestingly, this rate slows down significantly between 3800 m and 5000 m, which is the same depth over which the diameters had decreased and remained stagnantly small. Prior studies, such as LeMone and Zipser (1980) have attempted to analyze the correlation between velocity and diameter and have yielded little success. Therefore, it would be prudent to attempt a similar analysis when qualitatively analyzing these profiles, it does appear that there is at least some link between the two. Quantitatively, however, this link is not as evident. Figure 9 shows a plot of mean velocity versus diameter.

Figure 9. Relationship between continental updraft core diameter and mean vertical velocity
The coefficient of determination, $r^2$, was calculated to be 0.22, which can be interpreted that approximately 22% of the variation in mean vertical velocity can be explained by the diameter of the updraft. From that, the correlation coefficient was calculated to be 0.469, which is a moderate correlation between the two variables. The relationship between diameter and mean vertical velocity was then investigated at three different altitude levels based upon the vertical profiles of mean vertical velocity and diameter, and the results are summarized below in Table 8.

<table>
<thead>
<tr>
<th>Altitude Range (m)</th>
<th>$R^2$</th>
<th>$R$</th>
</tr>
</thead>
<tbody>
<tr>
<td>2500 – 3800</td>
<td>0.363</td>
<td>0.602</td>
</tr>
<tr>
<td>3800 – 5000</td>
<td>0.244</td>
<td>0.494</td>
</tr>
<tr>
<td>5000 – 6200</td>
<td>0.261</td>
<td>0.510</td>
</tr>
</tbody>
</table>

Table 8. Relationship between diameter and mean vertical velocity at three different altitude ranges; 2500m-3800m, 3800m-5000m, and 5000m-6200m

Up until 3800 m, approximately 36% of the variation in mean updraft velocity could be explained by the relationship that exists between updraft diameter and mean vertical velocity. Above this level, however, the updraft diameter becomes less influential in lieu of a different mechanism. Likewise, the relationship between updraft diameter and maximum velocity were investigated, and the results were summarized in Figure 10 and Table 9.
Figure 10. Relationship between diameter and maximum vertical velocity for cointnetal updraft cores

<table>
<thead>
<tr>
<th>Altitude Range (m)</th>
<th>$R^2$</th>
<th>$R$</th>
</tr>
</thead>
<tbody>
<tr>
<td>2500 – 3800</td>
<td>0.399</td>
<td>0.632</td>
</tr>
<tr>
<td>3800 – 5000</td>
<td>0.325</td>
<td>0.570</td>
</tr>
<tr>
<td>5000 – 6200</td>
<td>0.385</td>
<td>0.620</td>
</tr>
</tbody>
</table>

Table 9. Relationship between diameter and maximum vertical velocity at three different altitude ranges; 2500m-3800m, 3800m-5000m, and 5000m-6200m

Below 3800 m, 40% of the variation could be explained by updraft core diameter alone before dropping down to 32% between 3800 m and 5000 m. Interestingly here is that above 5000 m, the coefficient of variation rebounds back up to .385, indicating that updraft core diameter essentially can explain the same amount of variation as before the updraft diameters shrunk and the accelerations stagnated between 3800 m and 5000 m.
Lastly, the vertical profile of liquid water content was investigated and can be found in Figure 11:

![Vertical Profile of Continental Updraft Liquid Water Content](image)

Figure 11. Vertical profile of continental updraft core liquid water content

Analogously to the diameter profile, cloud liquid water content increases with altitude until 3800 m where it begins to rapidly decrease with altitude through 4200 m. It then rebounds above that point.

Using the same aircraft penetration dataset, there were 2071 unique downdrafts penetrated along the same flight legs, of which 1253 had diameters over 500 meters wide. This shows that there were over twice as many downdrafts as there were updrafts in those flight legs. The average diameter of the entire population of downdrafts sampled was
2180 m, with diameters of 2269.9 m, 2199.9 m, and 2073.1 m being found for Florida, Oklahoma, and South Dakota respectively, shown below in Figure 12:

![Continental Downdraft Diameters](image)

Figure 12. Continental downdraft core diameters from Florida, Oklahoma, and South Dakota thunderstorm penetrations

A one-way ANOVA with a confidence level of 95% yielded a p-value of 0.44, indicating that the difference in these population mean diameters was not significant. These diameters are much larger than the updraft diameters by over a kilometer and such difference is found to be statistically significant.

The mean average downdraft vertical velocity for the continental downdrafts was found to be 2.31 m/s, with the specific mean average downdraft vertical velocities for
South Dakota, Oklahoma, and Florida being 2.47 m/s, 2.38 m/s, and 2.36 m/s. Figure 13 captures these results:

![Continental Downdraft Mean Vertical Velocity](image)

Figure 13. Continental downdraft mean vertical velocity from Florida, Oklahoma, and South Dakota thunderstorm penetrations

Again, the positive axis for downdraft vertical velocities is defined such that they are positive if they are oriented towards the ground. When the one-way ANOVA with a confidence level of 95% was performed to check for significant difference between these means, a p-value of 0.25 was obtained, indicating no evidence that there was a significant difference between these population means.
The mean maximum downdraft velocity for the continental downdrafts was found to be 3.48 m/s, with values of 3.75 m/s, 3.65 m/s, and 3.54 m/s corresponding to the South Dakota, Oklahoma, and Florida updrafts respectively, captured in Figure 14:

Figure 14. Continental downdraft maximum vertical velocity from Florida, Oklahoma, and South Dakota thunderstorm penetrations

The one-way ANOVA with a 95% level of confidence yielded a p-value of 0.31, again indicating that there was no evidence to suggest a significant difference between the mean maximum velocities of the downdrafts at the three separate locations. Both the mean average vertical velocity and the mean maximum vertical velocity of the downdraft cores are less than their updraft counterparts. This difference again is found to be statistically significant.
For cloud liquid water content, captured by Figure 15 below, the mean value for the downdraft cores is 0.075 g/m³ with values of 0.087 g/m³ for Florida and 0.078 g/m³ for South Dakota. A much lower value of 0.045 was calculated for Oklahoma, which was found to be significantly different from the other two values by using two-sample t-tests. These values were all much smaller than their updraft core counterparts, and this difference is statistically significant.

![Continental Downdraft Liquid Water Content](image)

**Figure 15.** Continental downdraft liquid water content from Florida, Oklahoma, and South Dakota thunderstorm penetrations

Vertical profiles of diameter, velocity, and liquid water content were also computed for the downdraft cores. Because more downdraft cores were intercepted than updraft cores,
the vertical profiles could be divided into more altitude bins while keeping large enough sample sizes, and therefore the vertical resolution was even greater. Figure 16 shows the vertical profile of downdraft core diameter with respect to height.

![Vertical Profile of Continental Downdraft Core Diameters](image)

**Figure 16. Vertical profile of continental downdraft core diameters**

From 2100 m to 4600 m, the diameters had a tendency to increase with altitude before rapidly decreasing above that until about 4850 m. Above that point, diameters again increased with height until 5000 m, above which they again decreased with height. Figure 17 shows the profile of mean vertical velocity.
Figure 17. Vertical profile of continental downdraft core mean vertical velocity

Vertical velocity increases through 4200 m, decreases from there to 5000 m, and then increases above that. Likewise, Figure 18 shows the profile of maximum vertical velocity and the trend is similar.
Interestingly, around 3500 m the rate of increase of downdraft core diameter with height increases quite rapidly.

The vertical profile of liquid water content, shown in Figure 19, is the most erratic of all the vertical profiles computed for this thesis.
Figure 19. Vertical profile of continental downdraft liquid water content

Here, liquid water content increases until about 3500 m, decreases sharply above that until 4850 m, and then rapidly increases above that until 5000 m. Liquid water content decreases with altitude above that for the rest of the depth of the profile.

So far, thunderstorm updraft and downdraft core statistics have been derived for a new set of aircraft penetrations taken since the Thunderstorm Project. These new measurements shall be compared to those taken from various oceanic field campaigns, but first it will be useful to see how this dataset compares to the Thunderstorm Project data, as well as measurements obtained from other continental core penetrations.

Immediately, one important difference between this updated continental dataset and that from the Thunderstorm Project is the selection of convective events which were sampled. During the Thunderstorm Project, isolated thunderstorms that were in the midst
of their growth phase were targeted for penetration, within which would reside strong updrafts consistent with a growing storm (Byers and Braham 1948). This updated dataset comes from campaigns where such targeting did not occur, and the sample consists of penetration data from thunderstorms in all different stages of their lifecycles. Furthermore, the use of an inertial navigation system allows for more accurate vertical velocities to be calculated from this updated dataset than from the Thunderstorm Project. Lastly, updraft and downdraft cores were defined analogously to how they were in Zipser and LeMone (1980) in order for the dataset to be used for statistical comparisons with oceanic field campaigns. This is different than how they were defined in the Thunderstorm Project, which would oftentimes group separate yet closely-spaced updraft cores together as one single core. Due to this, it is anticipated that the cores analyzed in this experiment would have diameters smaller than those from the Thunderstorm Project.

The first significant difference between the datasets is the treatment of Florida data compared to that obtained from the continental interior. Byers and Braham (1949) came to the conclusion that the Ohio and Florida datasets were similar enough to be grouped together. Though Ohio data was not utilized in this thesis, when data from Oklahoma was analyzed, it was found that the differences in mean and maximum updraft velocities between Florida cores and those penetrated from Oklahoma are statistically significant. Therefore, Florida and Ohio may have needed to be treated as two separate populations. More in-situ data from Ohio is necessary to support this claim.

The diameters obtained from the Thunderstorm Project cores were about 1500 m wide for updrafts and 1000 m wide for downdrafts. This is about on par with the updrafts
encountered in the revised dataset, though almost half as wide as what was seen with continental downdrafts in this dataset.

The median updraft and downdraft core velocities from the Thunderstorm Project were 6.3 m/s and 5.8 m/s. These are considerably higher than the median velocities obtained from the updated continental data. Even when the data is split into two separate populations, those cores from Florida and those from the continental interior, none of the median velocities approach their Thunderstorm Project counterparts. Following the style of the Thunderstorm Project, and later Oceanic field campaigns, median updraft and downdraft core velocities for the strongest 10% of the cores were calculated. This yielded a median value of 7.39 m/s for updraft cores and 4.20 m/s for downdraft cores. Again, these values were notably smaller than their Thunderstorm Project counterparts. Split into the Florida versus continental interior populations, the medians were calculated to be 6.15 m/s for interior updraft cores and 8.44 m/s for Florida updraft cores. Yet again, these values were still smaller than their continental counterparts. Because there is no statistically significant variation in downdraft population mean vertical velocities between the three regions over the continents, there were not divided up.

The question that must be asked now is why such a difference exists. This author speculates that there should be two reasons for this disparity. The first of these reasons goes back to the sampling technique utilized in the Thunderstorm Project. The thunderstorms that were penetrated were specifically chosen if they were isolated and in their growing phase, and again it would be expected that these updrafts would be quite strong. The thunderstorms penetrated in the dataset utilized by this thesis, however, were
not discriminated against based on maturity or environment, and therefore it would be expected that there would be more variation in updraft and downdraft core velocities and diameters, as well as smaller mean and median values.

A second reason for the smaller median velocities of this dataset compared to the Thunderstorm Project is that it may not adequately sample the variety of vertical velocities and diameters that exist over the continents. The penetrations in this new dataset took place at altitudes ranging between 2500 m and 6000 m. Though this establishes a great vertical resolution of diameters and vertical velocities in this range, it leaves out lower altitudes where Thunderstorm Project data was heavily sampled and where much of the oceanic sampling took place.

The largest continental mean vertical velocity encountered in this dataset was 15.4 m/s from Oklahoma, which remains smaller than the largest found in the Thunderstorm Project. Furthermore, much greater magnitudes of vertical velocity have been found over the continental United States. Updraft vertical velocities with magnitudes as massive as 55 m/s have been observed by Musil et al. (1986) using aircraft penetration data. Are such measurements extraordinarily rare, or do they just occur frequently in levels outside of those sampled in this dataset? Though Musil et al. (1986) does not report the altitude at which this 55 m/s updraft velocity was measured, they point out that for 6 vertical kilometers vertical velocities exceeded 30 m/s. It turns out, however, that flights into supercells of this intensity are both taxing and dangerous, and therefore it is likely that the lack of updrafts this strong in the dataset utilized in this thesis simply under sampled them. Giangrande et al. (2013) produced vertical profiles of velocity using wind profilers,
and found that vertical velocities of both updraft and downdraft cores increase with height, and that stronger updrafts over 10 m/s are very common above 8000 m in altitude. Such regions were not sampled in the dataset utilized by this thesis, and this could account for lower values of updraft core maximum vertical velocities in Oklahoma.

The Thunderstorm Project was not the only field study that has produced a large dataset of continental updraft and downdraft core penetrations, though it does appear the only one to study subtropical continental interior thunderstorms. Anderson et al. (2005) investigated aircraft penetration data of continental tropical thunderstorms over Brazil in the Amazon basin, though found that their results were comparable to other tropical field campaigns that will be discussed in the next section.

As discussed a previous chapter, the first field campaign to be conducted over the oceans was GATE, which occurred in the Atlantic off the western coast of Africa. LeMone and Zipser (1980) noted that there were a few key differences in how measurements were taken between GATE and the Thunderstorm Project. Unlike the Thunderstorm Project where isolated thunderstorms in their growth phase were selectively sampled, GATE penetrations took place in both isolated thunderstorms and widespread disturbances, with thunderstorms at all points in their lifecycles being sampled. The dataset utilized in this thesis followed suit not favoring isolated clouds or convection in the growth phase. Furthermore, the three airplanes utilized in the GATE field campaign were equipped with inertial navigation systems, which were not yet developed back during the Thunderstorm Project. The use of an inertial navigation system is important, for it measures the vertical velocity of the aircraft in three
dimensions which allows for more accurate calculations of vertical velocity than were collected during the Thunderstorm Project Zipser and LeMone (1980). This inertial navigation system was used in the continental dataset used in this thesis, as well as each of oceanic field campaigns discussed in this section.

When analyzing data from GATE, Zipser and LeMone (1980) found that the median updraft and downdraft core diameters averaged around 1 km each. LeMone and Zipser (1980) discussed mean core velocities and found that the median mean updraft and downdraft core velocities for GATE were 2.9 m/s and 1.8 m/s respectively. These values are smaller than those calculated by the dataset gathered for this thesis. They also note that none of the mean downdraft and updraft core velocities were greater than 8 m/s, and no maximum updraft or downdraft core velocities had magnitudes greater than 15 m/s. In the updated continental dataset, roughly 3% of the mean updraft velocities exceeded 8 m/s, and 2.5% of the maximum updraft velocities exceeded 15 m/s, showing that stronger core velocities appear to exist over the continents.

Hurricanes data was discussed by Gray (1965), but this was before the advent of the inertial navigational system. Core properties were found by LeMone and Zipser (1980) to have been similar to those of GATE, and therefore a comparison with the updated continental dataset is not warranted here. The aircraft penetration data analyzed by Jorgensen et al. (1985) was collected by an aircraft with an inertial navigation system. It was found that hurricane updraft cores had average diameters of 1800 m, average mean velocity of about 2 m/s, and average maximum velocity of about 4 m/s. Like GATE, these values were smaller than those found in the updated continental dataset. Similar
values for oceanic downdraft cores were found to be 1800 m, 1.5 m/s, and 2.5 m/s, again, smaller than their continental counterparts. More modern hurricane updraft and downdraft core penetrations were collected and analyzed by Eastin et al. (2004). They found mean updraft and downdraft diameters were slightly smaller than those found by Jorgensen et al. (1985) with diameters of 1500 m, similar to continental updrafts but smaller than continental downdrafts gathered in the updated dataset. Median updraft core velocities were found to be 1.5 m/s while median downdraft velocities were found to be 1.4 m/s. Again, these values are smaller than their continental counterparts.

During TAMEX, updrafts and downdrafts were sampled from an environment disturbed by a mesoscale convective system, and it was found that the values were similar to those obtained from GATE (Jorgensen and LeMone, 1989). The updraft and downdraft diameters averaged around 1100 m, which were much smaller than those found with the continental data analyzed by this thesis. The mean updraft and downdraft core velocities were 2.4 m/s and 1.5 m/s respectively, which were also smaller than their continental counterparts. Maximum vertical velocity followed the same trend. The vertical profiles of diameter and vertical velocity were similar between TAMEX and GATE. For diameter, there was a very slight trend of increasing up until 2 km in TAMEX before decreeing slightly up to 3 km that was not evident in GATE. This could, however, be due to there being few updraft and downdraft cores sampled by TAMEX within these levels. A similar trend could be seen with TAMEX maximum vertical velocity, which slightly differed from that of GATE which was more constant with height. Again, this is likely due to under sampling of cores within the lowest 2 km during TAMEX. The
profiles for mean vertical velocity were very similar. Because the lowest level for the profiles for the continental dataset is 2.5 km, there is no real difference in how TAMEX profiles compare to the updated continental data compared with how GATE data compare to the continental dataset. Unlike GATE, however, data from TAMEX have brought forward profiles of liquid water content for updraft and downdraft cores, which can be found in Figure 5 of Jorgensen and LeMone (1989). This profile shows that cloud liquid water content increases from the surface to 2 km, decrease then until 3 km, increases through 5.5 km, and then sharply decreases through 6.6 km. They discuss that this final drop-off is rapid due to the fact that oceanic updrafts have difficulty carrying liquid water above the freezing level, which they noted to be around 5.3 km. From the continental cloud liquid water content profile constructed in the previous section, it is clear that the liquid water contents are much less over the continents than over the oceans between 3 km and 6 km, the vertical extent of the continental profile. Furthermore, the shape of the profile is a bit different, for there is a lot more variability of the values of cloud liquid water content than in TAMEX, though again this could be due to higher vertical resolution.

Updraft and Downdraft core statistics from EMEX were discussed by Lucas et al. (1994). It was found that the mean diameter of updraft cores was 1000 m and the mean diameter of downdraft cores was around 750 m. Again, these values are not only smaller than those acquired from the new continental dataset, they also show this trend of oceanic updraft cores having larger diameters than oceanic downdraft cores. For EMEX updraft core velocities, the average mean velocity was 2.2 m/s and the average maximum vertical
velocity was 3.2 m/s. Both of these values are markedly smaller in magnitude than those observed. The same trend could be seen with downdraft cores where the EMEX velocities were 1.5 m/s and 2.0 m/s for average mean velocity and average maximum velocity respectively, both of which were again smaller than their continental counterparts from South Dakota, Oklahoma, and Florida. The vertical profiles of diameter, mean vertical velocity, and maximum vertical velocity were, again, comparable to those obtained by GATE and TAMEX.

Lastly, TOGA COARE updraft and downdraft core properties were very similar to prior oceanic field experiments. This time, data from TOGA COARE was also analyzed so that velocities and cloud liquid water contents could be compared within the altitude range of the available continental data.

From aircraft penetration data, 1677 updrafts were collected, 880 of which had diameters greater than 500m and were used in this thesis. The average mean updraft core velocity of the TOGA COARE dataset, from within the altitude range of 2500 m to 6100 m, was found to be 2.25 m/s whereas the average maximum updraft core velocity was found to be 3.27 m/s. These, shown in Figure 20, were significantly smaller than their continental updraft counterparts.
The mean liquid water content of the TOGA COARE updraft over this altitude range was found to be 0.30 g/m³, which was significantly greater than the continental value of 0.03 g/m³. Figure 21 displays boxplots of this data, and Figure 22 shows the vertical profile of liquid water content.
Figure 21. Comparison of continental and oceanic mean liquid water content

Figure 22. Vertical profile of oceanic updraft core liquid water content
LWC values increase up until 4000 m and then decline sharply. This sharp decline is characteristic of oceanic convection, especially near and above the freezing level.

TOGA COARE downdraft cores had an average mean velocity of 2.11 m/s and an average maximum velocity of 2.90 m/s. These values were both significantly smaller than their continental counterparts. The liquid water content of the oceanic downdrafts was calculated to be 0.20 g/m$^3$, which was significantly larger than that calculated over the continents. Figure 23 shows the oceanic downdraft cloud liquid water content vertical profile, which is rather straightforward and decreases with height:

![Vertical Profile of Oceanic Downdraft Liquid Water Content](image)

Figure 23. Vertical profile of oceanic downdraft core liquid water content

As discussed in the opening literature review, authors have suggested a variety of different reasons why oceanic updrafts tend to be weaker than their continental
counterparts, though the scope of this thesis is to analyze the impact that entrainment plays. In particular, entrainment would limit buoyancy by leading to evaporative cooling of the updrafts, decreasing their temperatures until they equalize at the environmental temperature. By looking at figures XX and XX, there is a clear decrease in liquid water content above 3800m. Two atmospheric processes work to decrease liquid water content within clouds; precipitation and entrainment. Precipitation is obvious, for as rain falls out of clouds, there will be less liquid water in the air parcels. Entrainment would limit cloud liquid water by bringing dry environmental air into the parcel and evaporating liquid from the clouds. Both continental and oceanic thunderstorms yield precipitation, yet the decrease in oceanic updraft core liquid water content is more pronounced. If entrainment truly has more of an impact on oceanic convection, this would explain such a pronounced decrease in cloud liquid water content with height. Furthermore, the associated evaporative cooling would explain why oceanic updrafts tend to be slower. The next chapter will use atmospheric soundings to determine whether entrainment is more effective at reducing the buoyancy of continental or oceanic convection.
In the previous section, new continental updraft and downdraft core penetration data reaffirmed the idea that continental and oceanic convection are different in terms of core diameters, vertical velocity, and liquid water content. The question that now must be answered is what causes these differences? In the introduction, some possible explanations presented by previous authors were discussed, and several authors pointed to the role entrainment may play in reducing the buoyancy of oceanic updrafts. This explanation will be critiqued using data from atmospheric soundings over the Continental United States and from oceanic soundings over the Western Pacific Warm Pool.

While prior investigations analyzed soundings that were representative of specific field campaigns, they were associated with smaller sample sizes from which statistically significant results could not always be obtained. In order to accommodate a much larger sample size, continental and oceanic soundings that were associated with heavy precipitation were randomly selected, which is different from how previous studies handled soundings. Older studies gathered soundings from days during which penetrations occurred, and they were gathered to create a representative sounding of the affiliated field campaign. This is helpful because it allows us to see what differences occur in the soundings and how these differences may lead to the weaker corresponding updrafts over the oceans compared to over land. Instead, here random days with heavy
precipitation were chosen so that the soundings in the dataset would be associated with vigorous updrafts. Essentially, the goal is to find a sounding dataset such that the updrafts associated with the soundings would be of comparable magnitude over the continents and oceans. It could then be analyzed to see how continental and oceanic soundings whose corresponding updrafts are similar compare and contrast.

First, undiluted CAPE is examined both over the continents and over the oceans. From the sample of sounding days, it is found that the mean CAPE over the continental United States is 1865 J/Kg and the mean CAPE over the oceans is 2856 J/kg. These values may seem surprising compared to results such as Lucas et al (1994b) who found that CAPE values representative of the continents from the Thunderstorm Project and oceans from GATE were similar, but this is due to differences in sounding selection. Again, soundings from GATE and the Thunderstorm Project were not selected such that only those associated with strong updrafts were in the sample. Instead they were selected based on the dates, times, and locations of aircraft flight legs that penetrated updrafts; some of which were strong, others were weak. Because these soundings were specifically selected to coincide with the strongest updrafts, the finding of Lucas et al. (1994) must be recalled in which updrafts occurring in oceanic and continental environments with similar values of buoyancy were significantly more intense over the continents than over the oceans. As a corollary to this, updrafts of similar magnitude would need much more CAPE over the oceans than over the continents.

Continental soundings were also analyzed to determine if there was significant variation between the population means of soundings gathered from the Dakotas,
Oklahoma, and Florida. It was found that values of CAPE over Oklahoma were statistically different than their smaller counterparts in Florida and the Dakotas with a CAPE value of 2225.6 J/kg. This value was still significantly smaller than the oceanic CAPE values. These results are summarized in the boxplots in Figures 24 and 25 below:

![Boxplot of Continental and Oceanic Undiluted CAPE Values](image)

Figure 24. Continental and oceanic CAPE values as calculated by a reversible adiabatic process
Figure 25. Continental CAPE values from soundings taken in South Dakota, Oklahoma, and Florida as calculated by a reversible adiabatic process.

As for values of convective inhibition, it was found that with this sample of continental and oceanic soundings, much more CIN was evident over the continents. Figure 26 shows the boxplots for the corresponding CIN values.
The mean CIN for the continents was found to be 99.6 J/kg whereas the mean CIN over the oceans was found only to be 20.3 J/kg. This difference was statistically significant. There was no significant variation between the population mean CIN values from the three different locations of sounding acquisition over the continents.

Values of the level of neutral buoyancy (LNB) support previous observations that the region of positive buoyancy is much deeper over the oceans than over the continents. The mean LNB pressure level over the oceans was found to be 113mb, whereas the mean LNB value over the continents was 196mb. This difference, shown in figure 27 below, was statistically significant.
It is not atypical for oceanic regimes to have the positive region of CAPE extend much deeper into the atmosphere, so this is expected. In order for them to have similar magnitudes of updrafts to their continental counterparts, however, they would be expected to have larger density temperature deviations than those observed from typical oceanic soundings. Recall that it was pointed out by Lucas et al. (1994) that virtual temperature deviations tend to be greater in magnitude over the continents than over the oceans. Density temperature deviations are treated similarly to virtual temperature deviations. Under the assumption that entrainment plays a significant role in diluting updrafts, this would lead to weaker updrafts because the smaller oceanic temperature
deviation would be easier to overcome. Therefore, if it was assumed, as it is here, that oceanic updrafts and continental updrafts were of similar intensity, it would be expected that oceanic soundings associated with vigorous updrafts would have significantly larger density temperature deviations. This was found when comparing continental and oceanic soundings. The maximum density temperature difference found over the continents was 6.76°C which was smaller than the oceanic value of 7.79°C, shown in Figure 28 below:

![Figure 28. Continental and oceanic maximum density temperature deviations as calculated for a reversible adiabatic process](image)

This difference was statistically significant and matches what was anticipated. It turns out, however, that the soundings collected over Oklahoma had a mean maximum
temperature deviation of 7.05°C, which was significantly larger than population means of the soundings collected over Florida and the Dakotas. There was no statistically significant difference between the population mean maximum density temperature deviation found over Oklahoma and over the oceans.

Again, from the selection technique used in this thesis, it can be assumed that the updraft cores congruent with the soundings gathered from Oklahoma and oceanic storms are both strong and approximately similar in strength. The maximum temperature deviations are statistically similar between them, yet the CAPE values are significantly larger over the oceans than they are over Oklahoma. This could just be a byproduct of only analyzing maximum density temperature deviations. It turns out, however, that the mean density temperature deviation over the continents is 3.28°C and is 3.77°C over the oceans, shown below in Figure 29:
Figure 29. Mean continental and oceanic density temperatures as calculated for a reversible adiabatic process

Though this difference is notable, it is not statistically significant. It still stands, however, that in order for oceanic convection to have similar magnitudes of updrafts as continental updrafts, the aspect ratio is quite important.

At this point, entrainment of environmental air into the updraft core seems to be the most likely explanation as to why oceanic updrafts tend to achieve a smaller proportion of their maximum possible buoyancy compared to continental thunderstorms. In order to determine how much entrainment dilutes these continental and oceanic soundings, the effect of three different entrainment rates on reducing parcel buoyancy were computed. These rates are chosen arbitrarily, for any rate could have been chosen for the scope of this thesis. What is important is that these rates show that under different
magnitudes of mixing and entrainment, oceanic buoyancy is diluted more than continental buoyancy.

The first of these calculations assumes that only one percent of the environmental air was entrained into the updraft. It was found that under this circumstance, the mean continental CAPE value was calculated to be 1094.8 J/kg and the oceanic CAPE value was calculated to be 1136.2 J/kg, shown below in Figure 30:

![Figure 30](image)

Figure 30. Continental and oceanic CAPE values when calculated assuming that one percent of the environmental air is entrained into the updrafts

The difference between these two CAPE values was found not to be significant. The diluted CAPE value was divided by the undiluted CAPE value to calculate what
proportion of the original CAPE this entrainment rate would yield. It was found that this entrainment rate led to CAPE values that were on average 58% of their undiluted values over the continents and 44% over the oceans. The difference between these values was found to be statistically significant.

The second entrainment calculation assumed that the rising updraft core interacts with ten percent of the environmental air. This yielded a continental CAPE value of 166 J/kg and an oceanic CAPE value of 119.3 J/kg, shown below in Figure 31:

![CAPE Based on Lateral Entrainment Case 2](image)

Figure 31. Continental and oceanic CAPE values when calculated assuming that ten percent of the environmental air is entrained into the updrafts
This difference is statistically significant. When this much environmental air was mixed into the parcel, the CAPE of the continents begin to exceed that of the oceans, though it is clear that the buoyancy in both cases has been severely diluted. Continental soundings showed to only contain 13% of their original CAPE value whereas oceanic soundings showed much less with only 5% of their original buoyancy. Again, this difference is statistically significant.

While the prior two entrainment calculations assumed a lateral entrainment rate that was constant at all levels, the third entrainment rate attempted to replicate cloud top entrainment. As the air parcel rose, if it was below the 400 mb level, it was assumed to mix environmental air such that 1% of the air was environmental air, the other 99% was from the parcel itself. Above the 400mb level, however, the entrainment rate would spike such that the mixture in the parcel included 20% environmental air. It was found that in this case, the mean continental CAPE value was 723.7 J/kg and the mean oceanic CAPE value was 688.7 J/kg, shown below in Figure 32:
These values were not statistically different. This continental CAPE value was 42% of its undiluted value and the oceanic CAPE value was 23% of its original value. This difference was statistically different.

These entrainment CAPE calculations provide evidence that entrainment does indeed dilute oceanic soundings much more than it does for continental soundings, reducing buoyancy by reducing density temperature deviations. This means that oceanic updrafts would be heavily impacted through dilution of buoyancy as drier environmental air mixes with the moist updraft air. As a consequence, evaporative cooling would reduce the updraft temperatures, and likewise density temperatures, reducing the difference between the parcel and environmental temperatures. As liquid water evaporates, the
associated liquid water content profile shows a marked decrease with height. These processes combined explain why oceanic updrafts are weaker than continental updrafts.
Chapter 6: Conclusions

Following the analysis described in the previous chapters, several conclusions have been made about the differences between continental and oceanic convection.

**Continental Thunderstorm Findings**

![Diagram showing differences between updrafts and downdrafts in continental thunderstorms]

Figure 33. Magnitudes of mean diameter, vertical velocity, liquid water content, CAPE and entrainment CAPE as observed from continental updraft and downdraft cores
First, a new set of statistics for mid-latitude continental convection has been created by gathering data from five field experiments over the Dakotas, Oklahoma, and Florida. It was found that updraft and downdraft velocities and diameters were indeed greater than their oceanic counterparts, though smaller in magnitude than would be expected based on observations from within specific continental storms from past field campaigns. It is likely that this is the case due to sampling only having been done in a narrow altitude range (2500 m – 6000 m) outside of which larger and stronger updraft and downdraft cores have been found. Furthermore, the extremely vigorous updrafts, such as those found in supercells by Musil et al. (1986), are likely rare and left out of the sampling performed by the aforementioned field campaigns.
Next, Byers and Braham (1948) determined that the differences between Ohio and Florida thunderstorms sampled during the Thunderstorm Project were small enough that they could be merged into a single dataset for analysis. While Ohio data was not available for analysis in this thesis, it was found that there are statistically significant variations in updraft intensity in different regions of the continent. In particular, Oklahoma updrafts had velocities and liquid water content values that were significantly smaller than those found in the Dakotas or Florida. Again, this is not to say that updrafts tend to be weaker in Oklahoma, for some very strong updrafts have been noted in the introduction. Nevertheless, it would be dangerous for aircraft to attempt to penetrate these. Future studies should beware of treating all continental midlatitude storms as similar, and more research should be conducted to determine whether the strong Oklahoma updrafts studied by specific field experiments are normal or rare occurrences.

Cloud liquid water content was analyzed from thunderstorm penetration data, and it was found that there was no statistically significant difference between continental and oceanic values of cloud liquid water content. There were, however, notable differences in their vertical profiles of liquid water content such that over the oceans, cloud liquid water content increases with height up until the freezing level, above which it rapidly decreases. Continental liquid water content values increase over the whole profile, though there is a decrease noted from about 3800 m to 4200 m above the ground. Very quickly, continental values of LWC dominate those from over the oceans. While precipitation would eliminate much of the liquid water content over the ocean, this also lends evidence
that entrainment of dry air into oceanic updrafts is effective at limiting liquid water content as the liquid water is evaporated.

When analyzing soundings, it was found that soundings associated with rigorous updrafts over the midlatitudes and oceans were found to have similar density temperature deviations yet different values of CAPE and different depths of positive buoyancy. For an oceanic updraft to be similar in magnitude as a continental updraft, it had to have significantly more CAPE associated with it, as well as much greater density temperature deviations than would normally be expected from oceanic convection.

Lastly, the role of lateral and cloud top entrainment in reducing buoyancy over continental and oceanic thunderstorms was analyzed. It was found that entrainment had a much more significant impact on limiting sounding buoyancy over the oceans than the continents.
References


Parczewski, W., Intensity of precipitation and frequency of electric discharges in thunderstorms, Idojaras, 62, 189-193, 1958.


Appendix A: Updraft Selection Program

The following is the program, written in IDL, used to isolate individual updraft cores from time series data of vertical velocity, as well as calculate the values of the updraft core’s diameter and maximum vertical velocity, as well as updraft core averages of vertical velocity and liquid water content. This program defines an updraft core as having a vertical velocity of at least 1.0 m/s and a diameter of 500m. In order to isolate downdraft cores, this same program can be used, special consideration should be taken that downdrafts are defined as having a vertical velocity that is less than or equal to -1.0 m/s. Before running the following program, aircraft penetration data must be read in from a data file.

```
W=fltarr(n)
W=smooth(kkkkoppp, 5, /edge_truncate)

h=0
v=0
for i=0, n-1 do begin
  if (W(i) lt 1.0) then begin
    v=0
    goto, C1
  endif
  if (v eq 0) then begin
    h=h+1
    v=1
  endif
C1:
```

86
endfor
print, h
indi=fltarr(2,h)
indices=fltarr(2,h)
m=-1
v=0
for i=0, n-1 do begin
  if (v eq 1) then begin
    if (W(i) lt 1.0) then begin
      v=0
      indi(0,m)=i-1
    endif
  endif else begin
    if (W(i) ge 1.0) then begin
      v=1
      m=m+1
      indi(1,m)=i
    endif
  endelse
endfor
indices=rotate(indi,3)

index=fltarr(2)
maximum=fltarr(h)
c=2
maximum=fltarr(h)
average=fltarr(h)
distance=fltarr(h)
P=fltarr(h)
ALT=fltarr(h)
COi=fltarr(h)
FPi=fltarr(h)
mlat=fltarr(h)
mlon=fltarr(h)
entries=fltarr(h)
Oe=fltarr(h)
LW=fltarr(h)
LATMP=fltarr(h)
LONMP=fltarr(h)
for i=0, h-1 do begin
for j=0, 1 do begin
    index(j)=indices(i, j)
endfor

a=index(0)
b=index(1)
c=b-a+1.0
entries(i)=c
maximum(i)=max(W[a:b])
average(i)=mean(W[a:b])
LW(i)=mean(JJJJJJW[a:b])
distance(i)=map_2points(longitu(a), latitud(a), longitu(b), latitud(b), /meters)
P(i)=mean(SSSPRES[a:b])
alt(i)=mean(ALTITUD[a:b])

endfor

openu, lun, 'updraft_data.txt', /get_lun, /append
for i=0, h-1 do begin
    printf, lun, alt(i), P(i), maximum(i), average(i), LW(i), distance(i)
endfor
close, lun
Appendix B

The following program is written in IDL to calculate CAPE when presented with pressure, temperature, and mixing ratio values from an atmospheric sounding. This calculation calculates four values of CAPE. The first of these considers a process that is reversible and takes into consideration the effect of latent heat release during freezing. The concept is that entropy and water content is conserved as the parcel rises. The remaining three calculations take into consideration the effects of entrainment. The concept here is that as the parcel rises, entropy and total mixing ratio will be diluted as environmental air is mixed in with the parcel air.

```idl
pro calc_e, T, P, e, r, es, lv
    
    Rd=287.04
    Rv=461.50
    ep=Rd/Rv
    T0=273.15
    cpd=1005.7
    cpv=1870.0
    cl=4190.0
    Llv0=2.501E+6
    Llv=(cpv-cl)*(T-T0)+Llv0
    Liv=2.834E+6
    Tli1=273.15
    Tli2=268.15

    esl=1.003*exp(53.67957-6743.769/T-4.8451*alog(T))
    esi=1.003*exp(23.33086-6111.72784/T+0.15215*alog(T))
    es1=1.003*exp(53.67957-6743.769/Tli1-4.8451*alog(Tli1))
```

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es2=1.003*exp(23.33086-6111.72784/Tli2+0.15215*alog(Tli2))
lv1=(cpv-cl)*(Tli1-T0)+Llv0
lv2=Llv
if(T gt Tli1) then begin
  es=esl
  desdT=esl*(6743.769/T/T-4.8451/T)
lv=Llv
  goto,jump1
endif
if(T lt Tli2) then begin
  es=esi
  desdT=esi*(6111.72784/T/T+0.15215/T)
lv=Llv
  goto,jump1
endif
es=esl+(T-Tli1)/(Tli2-Tli1)*(es2-esl)
desdT=1.0/(Tli2-Tli1)*(es2-esl)
lv=lv1+(T-Tli1)/(Tli2-Tli1)*(lv2-lv1)
jump1: rs=ep*es/(p-es)
e=r/(r+ep)*p
dedT=0.0
if(e ge es) then begin
  e=es
  dedT=desdT
endif
end

pro calc_s,p,T,r,rs,rvap,Rl,s

  Rd=287.04
  Rv=461.50
  ep=Rd/Rv
  T0=273.15
  cpd=1005.7
  cpv=1870.0

  calc_e, T, P, e, r, es, lv

  pd=p-e
  rvap=ep*e/pd
  Rl=r-rvap
  s=((cpd+r*cpv)*alog(T)-Rd*alog(pd)-r*Rv*alog(e)-Rl*lv/T)/(1+r)
end
pro Calc_Temp,r0,s0,p,Tli1,Tli2,T,rs,rvap,Rl,Trhopar
  Rd=287.04
  Rv=461.50
  ep=Rd/Rv

  i=0
  T1=100.0
  calc_s,p,T1,r0,rs,rvap,Rl,s1
  f1=s1-s0
  T2=500.0
  calc_s,p,T2,r0,rs,rvap,Rl,s2
  f2=s2-s0
  jump1:  T=(T1+T2)*0.5
          calc_s,p,T,r0,rs,rvap,Rl,s
          f=s-s0
          i=i+1
          if(i gt 100) then begin
            print,i,T,s0,s
            goto,jump2
          endif
          if(abs(s-s0) le 0.001) then begin
            goto,jump2
          endif
          if(f*f1 gt 0.0) then begin
            T1=T
            f1=f
          endif else begin
            T2=T
            f2=f
          endelse
          goto,jump1
  jump2:  Trhopar=T*(1.0+rvap/ep)/(1.0+r0)
end

pro CAPE,n, dTrho, P, IMAX, BASE, CAPEP, CINP
  INBP=0
  INBR=0
  imax=0
  imay=0
  Rd=287.04
  contc:
  for j=(n-1),0,-1 do begin
    IF (dTrho(j) gt 0.0) then begin
      
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INBP=$((\text{j} > \text{inbp}) * \text{j} + (\text{J} \leq \text{inbp}) * \text{inbp})

\text{goto, conta}

\text{endfor}

\text{conta:}
\text{IMAX}=(\text{INBP} > 0) * \text{inbp} + (\text{inbp} \leq 0) * 0
\text{dTrho}[\text{IMAX}:\text{N}-1]=0
\text{if} (\text{dTrho}(\text{n}-2) > 0.0) \text{then begin}
\text{for} \text{j}=(\text{n}-1), 0, -1 \text{do begin}
\text{IF} (\text{dTrho}(\text{j}) < 0.0) \text{then begin}
\text{INBR}=(\text{j} > \text{inbr}) * \text{j} + (\text{J} \leq \text{inbr}) * \text{inbr}
\text{goto, cont}
\text{endif}
\text{endfor}
\text{cont:}
\text{IMAY}=(\text{INBR} > 0) * \text{inbr} + (\text{inbr} \leq 0) * 0
\text{dTrho}[\text{IMAY}:\text{N}-1]=-1.0
\text{inbp} = 0
\text{for} \text{j}=(\text{n}-1), 0, -1 \text{do begin}
\text{IF} (\text{dTrho}(\text{j}) \geq 0.0) \text{then begin}
\text{INBP}=(\text{j} > \text{inbp}) * \text{j} + (\text{J} \leq \text{inbp}) * \text{inbp}
\text{goto, contd}
\text{endif}
\text{endfor}
\text{contd:}
\text{IMAX}=(\text{INBP} > 0) * \text{inbp} + (\text{inbp} \leq 0) * 0
\text{dTrho}[\text{IMAX}:\text{N}-1]=0
\text{endif}

\text{NAP}=0.0
\text{PAP}=0.0
\text{CAPEP}=0.0
\text{If} (\text{inbp} > 0) \text{then begin}
\text{For} \text{j}=1, \text{inbp} \text{do begin} \quad \text{;changed from} \text{j}=1,\text{inbp}
\text{TVM}=0.5 \times (\text{dTrho}(\text{j}) + \text{dTrho}(\text{j}-1))
\text{PM}=0.5 \times (\text{P}(\text{j}) + \text{P}(\text{j}-1))
\text{base}(\text{j})=\text{Rd} \times \text{TVM} \times (\text{P}(\text{j}-1) - \text{P}(\text{j})) / \text{PM}
\text{endfor}
\text{for} \text{j}=1, \text{inbp} \text{do begin}
\text{if} (\text{base}(\text{j}) > 0.0) \text{then begin}
\text{PAP}=\text{PAP} + \text{base}(\text{j})
\text{endif else begin}
\text{NAP}=\text{NAP} + \text{base}(\text{j})
\text{endif}
\text{endfor}
n=NUMBER OF ENTRIES
openr, 1, "FILE.TXT"

LOC="oun"
P=fltarr(n) ;Pressure
HGHT=fltarr(n) ;Height
T=fltarr(n) ;Temperature
DWPT=fltarr(n) ;Dewpoint Temperature
RELH=fltarr(n) ;Relative Humidity
r=fltarr(n) ;Mixing Ratio
DRCT=fltarr(n) ;Wind Direction
SKNT=fltarr(n) ;Wind Speed
THTA=fltarr(n) ;Potential Temperature
THTE=fltarr(n) ;Equivalent Potential Temperature
THTV=fltarr(n) ;Virtual Potential Temperature

P1=0.0
HGHT1=0.0
T1=0.0
DWPT1=0.0
RELH1=0.0
r1=0.0
DRCT1=0.0
SKNT1=0.0
THTA1=0.0
THTE1=0.0
THTV1=0.0

; c=''
;readf, 1, c
;for k=0, n-1 do begin
; readf, 1, P1, HGHT1, T1, DWPT1, RELH1, r1, DRCT1, SKNT1, THTA1, THTE1, THTV1
; P(k)=P1
; :HGHT(k)=HGHT1
; T(k)=T1+273.15
; DWPT(k)=DWPT1
; RELH(k)=RELH1
; :r(k)=r1*0.001 ;convert mixing ratio to SI units
; DRCT(k)=DRCT1
; SKNT(k)=SKNT1
; THTA(k)=THTA1 ;O
; THTE(k)=THTE1 ;Oe
; THTV(k)=THTV1 ;Ov
; endfor
; endfor
; close, 1

c=''
readf, 1, c
for k=0, n-1 do begin
  readf, 1, P1, T1, r1
  P(k)=P1
  T(k)=T1+273.15
  r(k)=r1*0.001 ;convert mixing ratio to SI units
endfor
close, 1

Rd=287.04
Rw=461.50
ep=Rd/Rw
Tli1=273.15
Tli2=268.15
Trhoenv=fltarr(n)
s=fltarr(n)
for k=n-1,0,-1 do begin
calc_s,p(k),T(k),r(k),rs,rvap,R1,s1
Trhoenv(k)=T(k)*(1.0+rvap/ep)/(1.0+r(k))
s(k)=s1
endfor

Tpar1=fltarr(n)
Tpar2=fltarr(n)
Tpar3=fltarr(n)
Tpar4=fltarr(n)
Trhopar1=fltarr(n)
Trhopar2=fltarr(n)
Trhopar3=fltarr(n)
Trhopar4=fltarr(n)
Trhopar5=fltarr(n)
dTrho1=fltarr(n)
dTrho2=fltarr(n)
dTrho3=fltarr(n)
dTrho4=fltarr(n)
BASE=fltarr(n)
r0=r(0)
s0=s(0)
r1=r0
s1=s0
r2=r0
s2=s0
r3=r0
s3=s0
Trhopar1(0)=Trhoenv(0)
Trhopar2(0)=Trhoenv(0)
Trhopar3(0)=Trhoenv(0)
Trhopar4(0)=Trhoenv(0)
Trhopar5(0)=Trhoenv(0)
cpv=1870.0
cpd=1005.7
e0=r(0)*P(0)/(0.62198+r(0))
Tsat=(2840.0/(3.5*log(T(0))-log(e0)-4.805)+55.0)
Plcl=P(0)*(Tsat/T(0))^((Cpd+r(0)*Cpv)/(Rd*(1.0+(r(0)/ 0.62198)))))
print, plcl
for k=1,n-1,-1 do begin
Calc_Temp,r0,s0,p(k),Tli1,Tli2,T,rs,rvap,Rl,Trhopar
Tpar1(k)=T
Trhopar1(k)=Trhopar
dTrho1(k)=Trhopar1(k)-Trhoenv(k)
Calc_Temp,r1,s1,p(k),Tli1,Tli2,T1,rs,rvap,Rl,Trhopar
Tpar2(k)=T
Trhopar2(k)=Trhopar
dTrho2(k)=Trhopar2(k)-Trhoenv(k)
r1=r1*0.99+r(k)*0.01
s1=s1*0.99+s(k)*0.01
Calc_Temp,r2,s2,p(k),Tli1,Tli2,T1,rs,rvap,Rl,Trhopar
Tpar3(k)=T
Trhopar3(k)=Trhopar
dTrho3(k)=Trhopar3(k)-Trhoenv(k)
r2=r2*0.9+r(k)*0.1
s2=s2*0.9+s(k)*0.1

Calc_Temp,r3,s3,p(k),Tli1,Tli2,T1,rs,rvap,Rl,Trhopar
if(p(k) ge 400.0) then begin
  frac=0.01
endif else begin
  frac=0.2
endelse
Tpar4(k)=T1
Trhopar4(k)=Trhopar
dTrho4(k)=Trhopar4(k)-Trhoenv(k)
r3=r3*(1 frac)+r(k)*frac
s3=s3*(1 frac)+s(k)*frac

endfor

CAPE,n, dTrho1, P, IMAX, BASE, CAPEP, CINP
CAPE1=CAPEP
CIN1=CINP
Index1=IMAX
LNB1=P(Index1)
Depth1=PLCL-P(Index1)

CAPE,n, dTrho2, P, IMAX, BASE, CAPEP, CINP
CAPE2=CAPEP
CIN2=CINP
Index2=IMAX
LNB2=P(Index2)
Depth2=Plcl-P(Index2)

CAPE,n, dTrho3, P, IMAX, BASE, CAPEP, CINP
CAPE3=CAPEP
CIN3=CINP
Index3=IMAX
LNB3=P(Index3)
Depth3=Plcl-P(Index3)
CAPE, n, dTrho4, P, IMAX, BASE, CAPEP, CINP
CAPE4 = CAPEP
CIN4 = CINP
Index4 = IMAX
LNB4 = P(Index4)
Depth4 = Plcl - P(Index4)

print, CAPE1, CIN1, LNB1, depth1
Print, CAPE2, CIN2, LNB2, depth2
Print, CAPE3, CIN3, LNB3, depth3
print, CAPE4, CIN4, LNB4, depth4

; openu, lun, 'Continental_Soundings.txt', /get_lun, /append
; printf, lun, LOC, CAPE1, CAPE2, CAPE3, CAPE4, CIN1, CIN2, CIN3, CIN4, LNB1, LNB2, LNB3, LNB4, PLCL, depth1, depth2, depth3, depth4
; close, lun
end