Calhoun
Institutional Archive of the Naval Postgraduate School

Calhoun: The NPS Institutional Archive

DSpace Repository

Theses and Dissertations 1. Thesis and Dissertation Collection, all items

2005-03

A case study of insitu-aircraft observations in a waterspout producing cloud

Baskin, Clayton M.

Monterey California. Naval Postgraduate School

http://hdl.handle.net/10945/2320

Downloaded from NPS Archive: Calhoun

DUDLEY
KNOX
LIBRARY

Calhoun is a project of the Dudley Knox Library at NPS, furthering the precepts and goals of open government and government transparency. All information contained herein has been approved for release by the NPS Public Affairs Officer.

Dudley Knox Library / Naval Postgraduate School
411 Dyer Road / 1 University Circle
Monterey, California USA 93943

http://www.nps.edu/library

NAVAL POSTGRADUATE SCHOOL

MONTEREY, CALIFORNIA

THESIS

A CASE STUDY OF INSITU-AIRCRAFT OBSERVATIONS IN A WATERSPOUT PRODUCING CLOUD

by

Clayton M Baskin

March 2005

Thesis Advisor:	Haflidi Jonsson
Co-Advisor:	Wendell Nuss

Approved for public release; distribution is unlimited.

THIS PAGE INTENTIONALLY LEFT BLANK

REPORT DOCUMENTATION PAGE	*Form Approved OMB No. 0704-0188*

Public reporting burden for this collection of information is estimated to average 1 hour per response, including the time for reviewing instruction, searching existing data sources, gathering and maintaining the data needed, and completing and reviewing the collection of information. Send comments regarding this burden estimate or any other aspect of this collection of information, including suggestions for reducing this burden, to Washington headquarters Services, Directorate for Information Operations and Reports, 1215 Jefferson Davis Highway, Suite 1204, Arlington, VA 22202-4302, and to the Office of Management and Budget, Paperwork Reduction Project (0704-0188) Washington DC 20503.

1. AGENCY USE ONLY *(Leave blank)*	**2. REPORT DATE** March 2005	**3. REPORT TYPE AND DATES COVERED** Master's Thesis

4. TITLE AND SUBTITLE: A Case Study of Insitu-Aircraft Observations in a Waterspout Producing Cloud	**5. FUNDING NUMBERS**
6. AUTHOR(S) Clayton M Baskin	
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) Naval Postgraduate School Monterey, CA 93943-5000	**8. PERFORMING ORGANIZATION REPORT NUMBER**
9. SPONSORING /MONITORING AGENCY NAME(S) AND ADDRESS(ES) N/A	**10. SPONSORING/MONITORING AGENCY REPORT NUMBER**

11. SUPPLEMENTARY NOTES The views expressed in this thesis are those of the author and do not reflect the official policy or position of the Department of Defense or the U.S. Government.

12a. DISTRIBUTION / AVAILABILITY STATEMENT Approved for public release; distribution is unlimited.	**12b. DISTRIBUTION CODE**

13. ABSTRACT (maximum 200 words)

An analysis of in-situ aircraft observations collected in the parent cloud of a waterspout is presented. Previous waterspout studies were confined mainly to photometric and model simulated data, no in-situ observations were made internal to the parent cloud. On 27 June 2002 the Cooperative Institute for Remotely Piloted Aircraft Studies (CIRPAS) UV-18A Twin Otter aircraft collected observations in a cloud that had developed in a cloud line, located approximately 15km south of Key West, and that formed a waterspout. This study attempts to analyze the waterspout formation process using these data and through a series of scale interactions, from the synoptic scale down to the individual cloud scale. Based upon the analyzed data a hypothetical formation process is developed.

The background synoptic scale flow is shown to establish the necessary ambient shear as a key factor in the waterspout formation. The orientation of mesoscale convergent boundaries and thermodynamic processes, internal to the cloud, proved to be an essential factor in developing the vertical motion patterns necessary for formation of an organized circulation in the shear region and to provide the tipping and stretching of the resultant vortex necessary to account for the waterspout formation. This is consistent with conclusions derived from previous studies.

14. SUBJECT TERMS Waterspout, Aircraft Data, CIRPAS, Synoptic Analysis, Sea Surface Temperature	**15. NUMBER OF PAGES** 55
	16. PRICE CODE

17. SECURITY CLASSIFICATION OF REPORT Unclassified	**18. SECURITY CLASSIFICATION OF THIS PAGE** Unclassified	**19. SECURITY CLASSIFICATION OF ABSTRACT** Unclassified	**20. LIMITATION OF ABSTRACT** UL

NSN 7540-01-280-5500

Standard Form 298 (Rev. 2-89)
Prescribed by ANSI Std. 239-18

THIS PAGE INTENTIONALLY LEFT BLANK

Approved for public release; distribution is unlimited.

A CASE STUDY OF INSITU-AIRCRAFT OBSERVATIONS IN A WATERSPOUT PRODUCING CLOUD

Clayton M. Baskin
Captain, United States Air Force
B.S., University of South Alabama, 1997

Submitted in partial fulfillment of the
requirements for the degree of

MASTER OF SCIENCE IN METEOROLOGY

from the

NAVAL POSTGRADUATE SCHOOL
March 2005

Author:	Clayton M Baskin
Approved by:	Haflidi Jonsson Thesis Advisor
	Wendell Nuss Co-Advisor
	Philip A. Durkee Chairman, Department of Meteorology

THIS PAGE INTENTIONALLY LEFT BLANK

ABSTRACT

An analysis of in-situ aircraft observations collected in the parent cloud of a waterspout is presented. Previous waterspout studies were confined mainly to photometric and model simulated data, no in-situ observations were made internal to the parent cloud. On 27 June 2002 the Cooperative Institute for Remotely Piloted Aircraft Studies (CIRPAS) UV-18A Twin Otter aircraft collected observations in a cloud that had developed in a cloud line, located approximately 15km south of Key West, and that formed a waterspout. This study attempts to analyze the waterspout formation process using these data and through a series of scale interactions, from the synoptic scale down to the individual cloud scale. Based upon the analyzed data a hypothetical formation process is developed.

The background synoptic scale flow is shown to establish the necessary ambient shear as a key factor in the waterspout formation. The orientation of mesoscale convergent boundaries and thermodynamic processes, internal to the cloud, proved to be an essential factor in developing the vertical motion patterns necessary for formation of an organized circulation in the shear region and to provide the tipping and stretching of the resultant vortex necessary to account for the waterspout formation. This is consistent with conclusions derived from previous studies.

THIS PAGE INTENTIONALLY LEFT BLANK

TABLE OF CONTENTS

THIS PAGE INTENTIONALLY LEFT BLANK

LIST OF FIGURES

THIS PAGE INTENTIONALLY LEFT BLANK

LIST OF TABLES

THIS PAGE INTENTIONALLY LEFT BLANK

ACKNOWLEDGMENTS

First and foremost I want to thank my wife and children for their undying love and support through this process. Without your love and support I would not have completed this school, you are the reason I live each day.

To Haf, your definition of serendipity will forever be with me. I have to say thank you for collecting and saving the data related to this study. You provided the mentoring and insight that this, average at best, student needed to complete this project. The complete serendipity of the situation still amazes me to this day.

Professor Nuss, thanks for being so patient throughout this process, you provided the insight I needed to see this study through.

Jeff Jarry and John Sandifer, the leper colony, guys it's been a tough road, but we did it. Thanks for all your help and support throughout our time here. You guys brought a new outlook on the educational process, gentlemen it has been fun, well as fun as school can be.

THIS PAGE INTENTIONALLY LEFT BLANK

I. INTRODUCTION

A major challenge faced by weather forecasters in the Florida coastal regions is forecasting waterspouts. High densities of military bases exist along the Florida coast; so improved understanding of waterspouts has obvious implications for both resource protection and daily activities on these bases. Waterspouts have a dramatic impact on base operations. If one is observed with-in 5nm of a base, a tornado warning is issued. This warning prompts numerous responses from base personnel, not the least of which is the halting of all flight operations. Although waterspouts occur frequently along these coastal regions, relatively few studies have been done to increase understanding of their formation. The climatology of waterspout occurrences is not well documented but is estimated to be in the hundreds per year in the Key West region alone. Previous research focused mainly on photometric studies and numerical modeling. The relative rarity, violent nature and location of occurrence have impeded the collection of relevant data in and around waterspouts. This study will describe a dataset collected by the Center for Interdisciplinary Remotely-Piloted Aircraft Studies' (CIRPAS) Twin Otter aircraft in a cloud that spawned a waterspout near the Florida Keys.

A. BACKGROUND INFORMATION

Golden (1974) defined a waterspout as "an intense columnar vortex (not necessarily containing a funnel shaped cloud) of small horizontal extent over the water". Davies-Jones et al. (2001) defined a waterspout as "a tornado over a body of water". Tornadoes are well-studied phenomena with vast quantities of data available, while waterspouts remain rarely studied. The current literature divides tornadoes into two distinct categories, Type I and Type II. Type I tornadoes are defined as tornadoes that form within a mesocyclone (Davies-Jones et al. 2001). This is the classic destructive tornado. Type II tornadoes are relatively weak columnar vortexes that form along a weak boundary or wind shift line and are not associated with a mesocyclone (Davies-Jones et al. 2001). Waterspouts typically fall into the Type II category. This research will compare the data collected by the CIRPAS Twin Otter to previously accomplished studies of waterspouts, and draw some comparisons to the Type II tornado.

Classic supercell tornados develop in environments that show identifiable synoptic forcing with considerable instability and wind shear. Waterspouts typically form in environments that lack the low-level instability and wind shear that are typical of tornado producing environments (Golden 1974); thus hindering the ability to forecast development and intensity of waterspouts. Previous research shows that the primary influence of synoptic scale flow, on waterspout development, is to control convective cloud line development in the Lower Keys (Golden 1974). Chapter II will include a discussion of the synoptic environment on the day in question.

Davies-Jones et al. (2001) note that Type II tornados typically form along stationary or slowly moving wind-shift lines. Several waterspout studies make the consistent observation that a bulk of observed waterspouts occur along gust fronts, sea breeze fronts or outflow boundaries. In this study, evidence will show the parent cloud to the waterspout was at the intersection of two convergent boundaries when the waterspout was detected. One of those convergent boundaries is an outflow boundary originating from a convective complex north of Key West. Satellite data, augmented by radar data, is the primary evidence for this. The other convergent boundary appears to have origins in a sharp thermal gradient in sea surface temperatures. It also may be seen in satellite images, and to the aircraft crew it revealed itself as a line of cumulus clouds. In the GATE waterspout study by Simpson et al. (1986), the formation of several waterspouts along the intersection of two boundaries was noted with the cumulus line located over a maximum in sea surface temperature gradient. Sea surface temperature data will be presented that indicates the proximity, of the cloud line under study, to a maximum in sea surface temperature gradient. Comparisons will be drawn between observed data in this study and modeled clouds from the Day 186 GATE observations. Detailed analysis of aircraft observations collected during this study will be presented in Chapter III, along with comparisons to the previous studies.

B. COLLECTED DATA

The CIRPAS Twin Otter aircraft collected the data on 27 June 2002 approximately 15km south-southwest of Key West. Collection times for the data were 1715-1856Z, on 1-second intervals. The bulk of the data are obtained in and around the parent cloud with limited data in the sub-cloud region. Recorded quantities include:

latitude, longitude, altitude, air temperature, dew point, static pressure, dynamic pressure and liquid water content (LWC). Calculated quantities analyzed include wind speed/direction, vertical velocities, and equivalent potential temperature.

C. GOALS

The goal of this paper is to further the understanding of thermodynamic and shear structures within and surrounding the parent cloud of a waterspout. A better understanding of the parent cloud structure will provide insight into the formation process. Modeling the formation process will aid meteorologists in developing forecast strategies for waterspouts. Improved waterspout forecasting skill will assist the Department of Defense in both resource protection and optimization of operations in coastal regions.

THIS PAGE INTENTIONALLY LEFT BLANK

II. BACKGROUND ENVIRONMENTAL DATA

A. SYNOPTIC ANALYSIS

Golden (1974) suggested the primary influence of the synoptic scale patterns, on waterspout formation, is to control the convective cloud line development. While there have been no definitive studies that can link specific synoptic situations to waterspout occurrence, several studies draw conclusions about general synoptic scale environments and their propensity to waterspout development. Golden (1974) noted several synoptic scale characteristics that affected the formation processes of a cloud line:

- Strong subsidence in the 1000-600mb layer will act to suppress cumulus development.
- Strong cyclonic conditions will increase the boundary layer winds and vertical wind shear, disrupting the differential surface heating mechanism necessary for cumulus growth.
- Outbreaks of numerous, or strong waterspouts, have been attributed to regimes that consist of weak, but well defined, trough lines in the lower troposphere.

Additionally, through field analysis and post-observation research Golden (1974) developed synoptic scale empirical criteria favorable for waterspout development:

- An approaching weak synoptic scale disturbance accompanied by weak convergence and positive absolute vorticity.
- Weak vertical wind shear in the lower troposphere.
- Moist and convectively unstable sounding profiles below at least 850mb, more typically 700mb, with substantial drying above. Often there are notable areas of adiabatic or super-adiabatic lapse rates on the sounding profiles. These convectively unstable layers are typically found in the sub-cloud region.

For the purposes of this study the synoptic scale analysis was based on the National Weather Service (NWS) facsimile charts. Analyzed charts include the 12Z 27 June 02 and 00Z 28 June 02 upper air analysis. A brief overview of the synoptic environment will be presented with emphasis on the lower troposphere. Section D will address the analysis of the Key West skew-t diagrams assumed to be representative of the mesoscale environment.

1. 300mb/500mb Analysis

The 300mb analysis for the period is characterized by a high amplitude ridge over the north central US and a broad trough over the northeastern US. A short wave ridge is located over southern Florida through western Cuba. The ridge shows little movement over the period but does flatten out by 00Z 28 June 02. Winds over southern Florida and Gulf of Mexico are characterized as 20-30 knots from the west through southwest.

The 500mb analysis is very similar to 300mb with exception to the short wave ridge. The ridge is centered over west central Florida at this level. Winds are generally from the southwest at 10-15kts. The temperature pattern over the south Florida region is horizontally homogeneous with no thermal advection evident.

2. 700mb Analysis

The 700mb analysis for 12Z 27 June 02 (Fig.1) shows a broad ridge over the north central US and a broad trough over the northeastern US. The short wave ridge mentioned at 500mb is reflected as a closed high centered over the north central Gulf of Mexico extending southeast to south Florida. The temperatures are horizontally homogenous with no thermal advection in the region. Winds over central and south Florida are from the west and northwest at 5-10kts. By 00Z 28 June 02 the closed high has progressed east-southeast and is now centered over south Florida. Winds over central and south Florida are from the north-northeast at 5-10kts.

3. 850mb Analysis

On the 850mb analysis, 12Z 27 June 02 (Fig.2), the dominant feature is a closed high centered off the coast of North Carolina. An associated ridge extends southwest over southern Florida. The orientation of the ridge produces easterly winds over the Straits of Florida, becoming southerly over the southeastern Gulf of Mexico. Wind speeds are 10kts over the region, with no thermal advection evident. The pattern remains similar through 00Z 28 June 02.

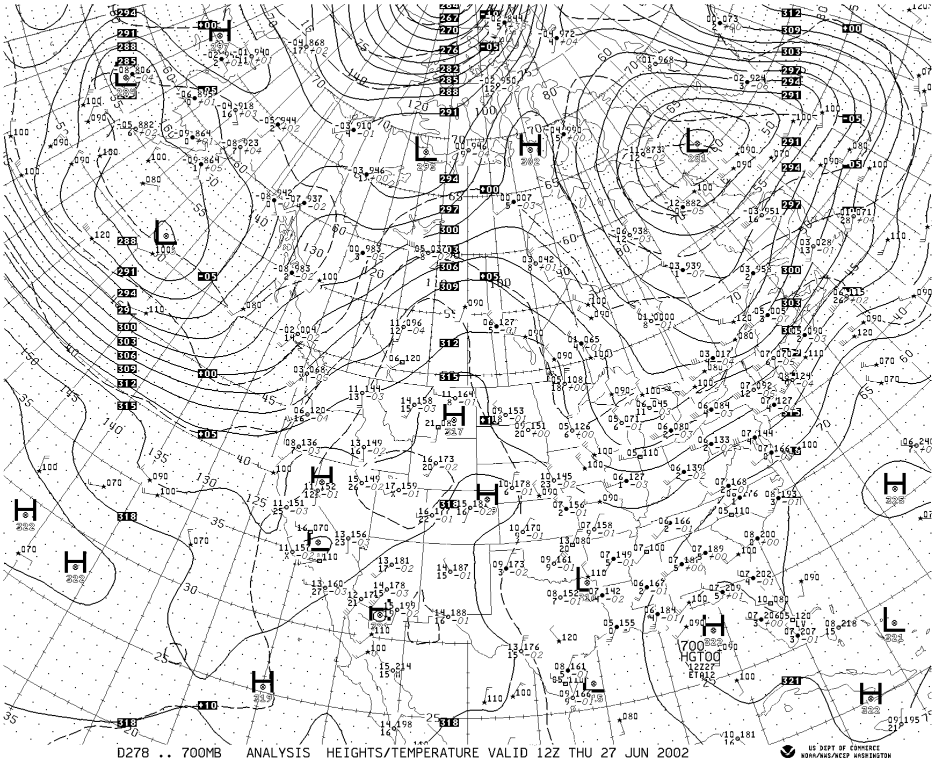


Figure 1. 700mb analysis 12Z 27 June 02

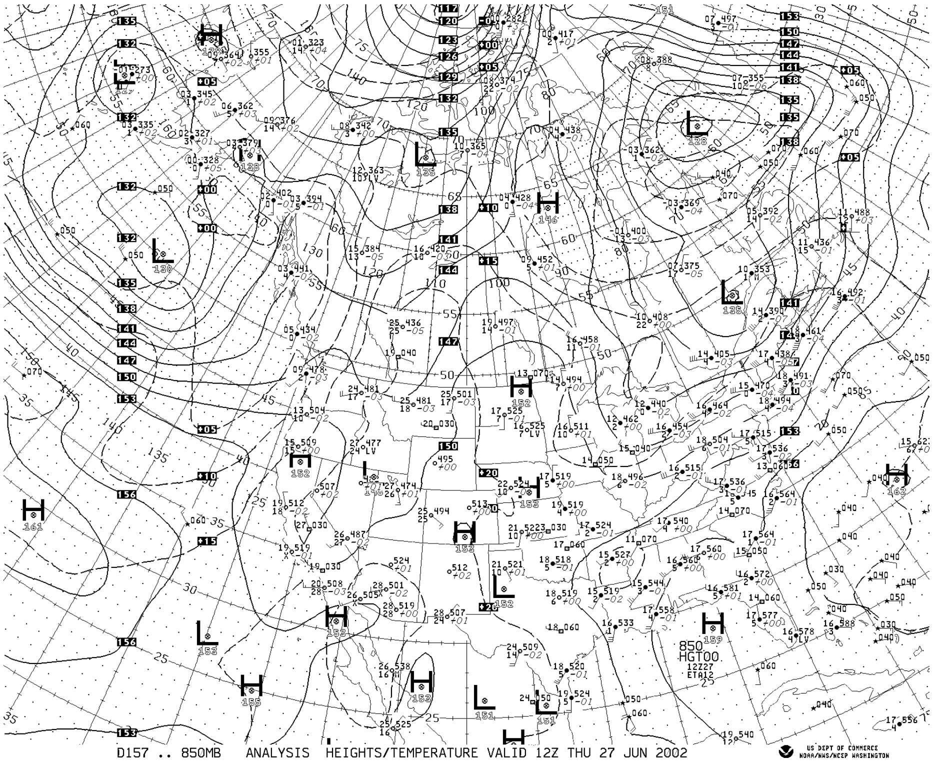


Figure 2. 850mb analysis 12Z 27 June 02

4. Surface Analysis

The surface analysis was based on the NWS facsimile charts (Fig.3), supplemented by the National Center for Environmental Prediction Atlantic Ocean analysis. The dominant synoptic scale surface feature for this period is a subtropical high pressure located in the central Atlantic around 30° north. A ridge, associated with the subtropical high, extends to the west in a manner similar to the 850mb ridge. This orientation produces easterly winds through the Straits of Florida, becoming southeasterly in the central Gulf of Mexico. The pressure analysis indicates a slight weakening of the ridge influencing the region. A review of the Key West surface observations, for 27 June 02, shows that Key West maintained 5-10 knot winds from the east through southeast throughout the day. Also of note in the observations, the surface pressure began falling in the Key West region after 1800Z, corresponding to the pressure analysis on the synoptic surface charts.

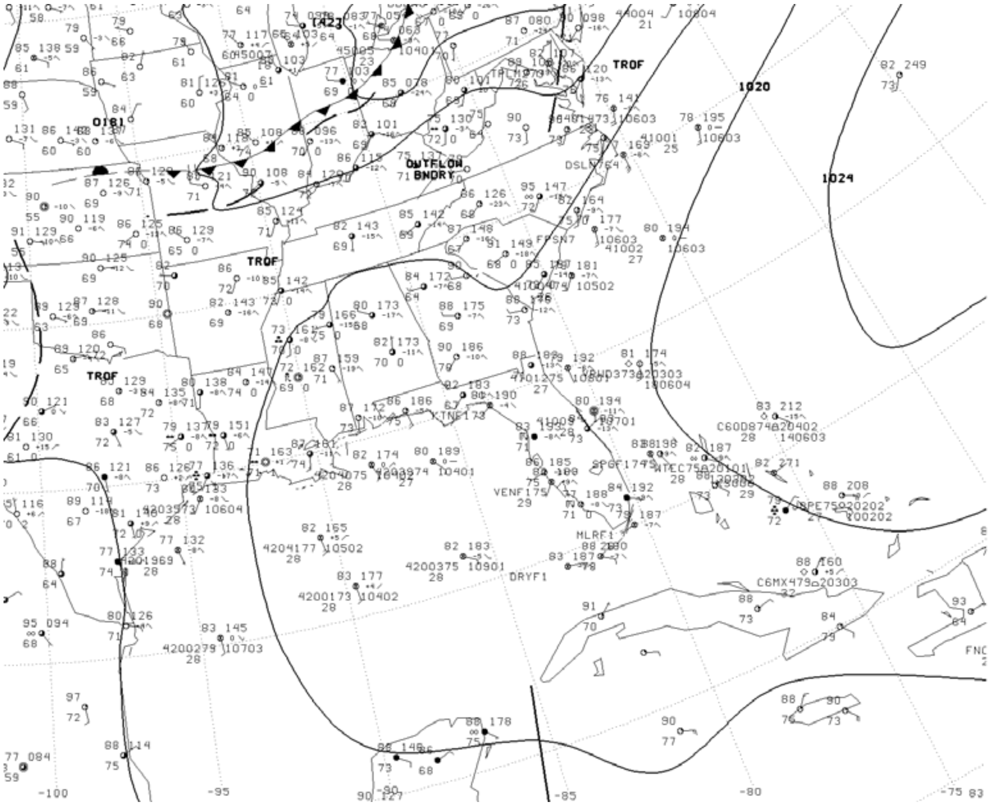


Figure 3. Surface Analysis 18Z 27 June 02

B. SATELLITLE AND SEA SURFACE TEMPERATURE ANALYSIS

1. Sea Surface Temperature Analysis

The Sea Surface Temperature (SST) analysis, presented in Figure 4, is derived from the Advanced Very High Resolution Radiometer (AVHRR) sensor. The data are 48 hour averages covering the period of 26 June 02 through 27 June 02, with 14km resolution. For presentation purposes the data were downloaded and plotted using the MATLAB program. A prominent area of 29°C temperatures is noticed southeast of Key West, upwind (at the surface) of the aircraft operations area. A sharp SST gradient is immediately south of the islands along the 81-west longitude line. Shallow water is believed to be the primary reason for the increased temperatures. Increased SST in this region is hypothesized by Golden (1974) to be the primary mechanism for cloud line development there. Cloud line development is noted on satellite imagery originating over the region of sharp SST gradient. Analysis of that will be presented in the following section.

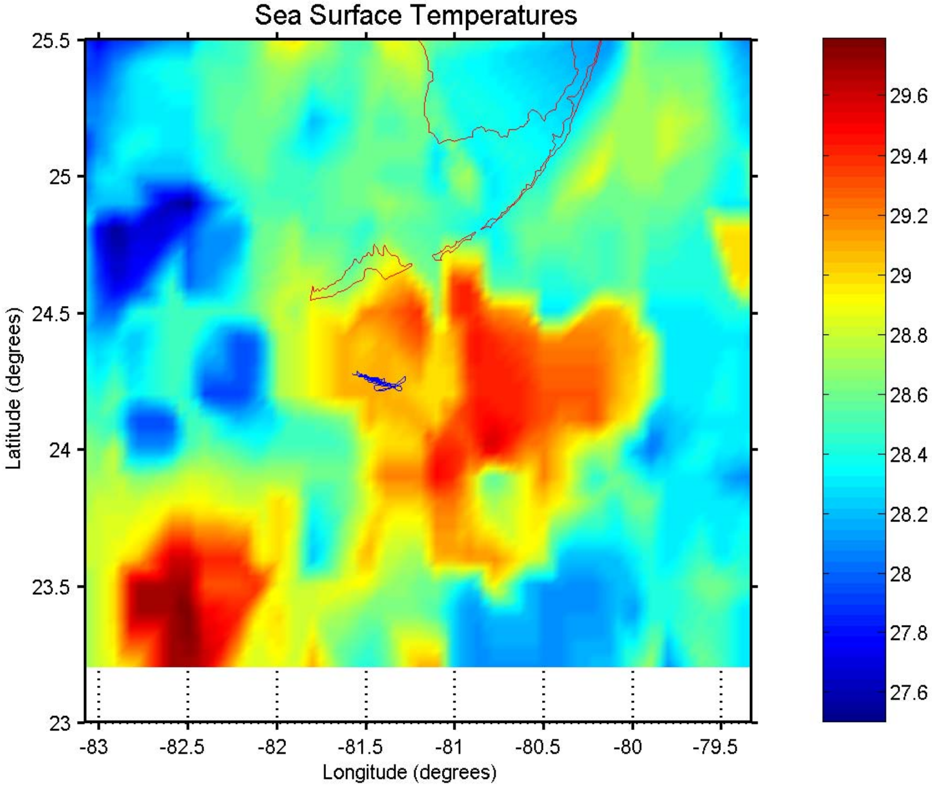


Figure 4. Sea Surface Temperature analysis 27 June 02 from AVHRR. Aircraft flight path plotted in Blue. Data courtesy of NOAA Comprehensive Large Array-data Stewardship web site: http://www.saa.noaa.gov/nsaa/products/welcome (Last Accessed March 2005)

2. Satellite Imagery Analysis

Satellite analysis was conducted using a combination of GOES 8 imagery and AVHRR data. The GOES 8 imagery was utilized to view time-lapse loops. AVHRR data were used for higher resolution analysis. Figure 5 is an image from the AVHRR sensor collected on 27 June 02 at 1910Z, approximately 30 minutes after the waterspout encounter. The storm position was determined using Global Positioning System coordinates from the aircraft. As indicated, in Figure 5, the storm is located at the intersection of 2 convergent boundaries. A large convective complex north of the Florida Keys generates the first convergent boundary, labeled "Outflow boundary", in Figure 5. Using the GOES 8 loops the boundary can be seen propagating south with convective development along it. The second boundary, labeled “Convergent Boundary”, is a convergent boundary with origins in the region of the sharp SST gradient noted in Sec II.B.1. Careful viewing of the GOES 8 loop reveals this convergent boundary develops in the vicinity of the SST gradient and propagates westward in the mean low-level flow. Convection develops along the boundary as it propagates. This arrangement of features is similar to day 186 of the GATE experiment (Simpson et. al. 1986). Correlations between the findings of the GATE experiment and data collected in this study will be presented in Section IV.

C. KEY WEST SKEW-T ANALYSIS

Skew-T diagrams for Key West were analyzed and assumed to be representative of the mesoscale environment. All available upper air observations were analyzed over the 27 June 02 00Z and 28 June 00Z period. The 12Z upper air observation for 27 June 02 was unavailable from Key West, data from Miami, Fl were used instead. Figure 6 shows the 28 June 02 00Z skew-t diagram for Key West Florida, this sounding was chosen as the most representative of the soundings based on comparisons of thermal structure and wind data. Thermal structure was analyzed for all available soundings and each exhibited a similar structure. Soundings from 00Z 27 June 02 and 28 June 02 were plotted against each other for comparison, the 28 June sounding exhibited more thermal instability relative to the 27 June sounding.

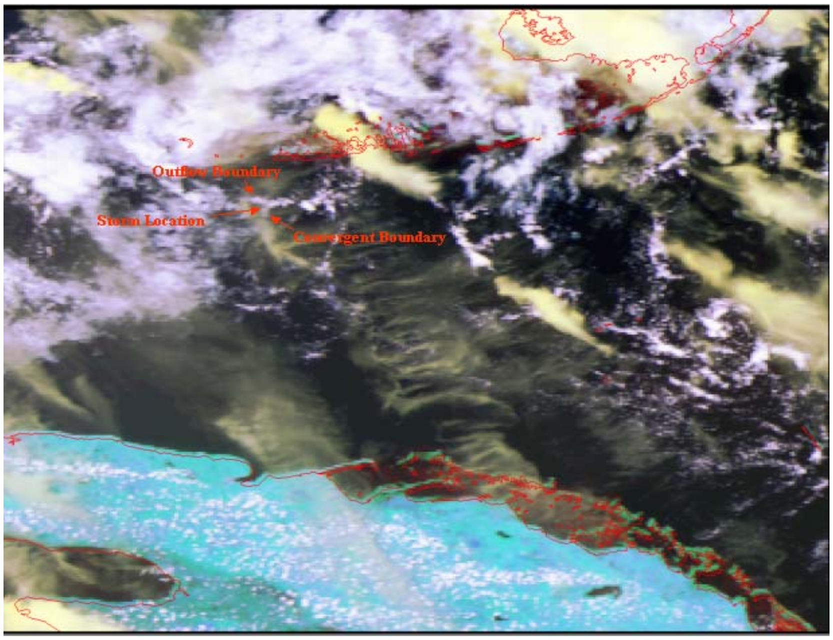


Figure 5. Satellite Imagery from AVHRR 27 June 02 1910Z.
Data courtesy of NOAA Comprehensive Large Array-data Stewardship web site: http://www.saa.noaa.gov/nsaa/products/welcome (Last Accessed March 2005)

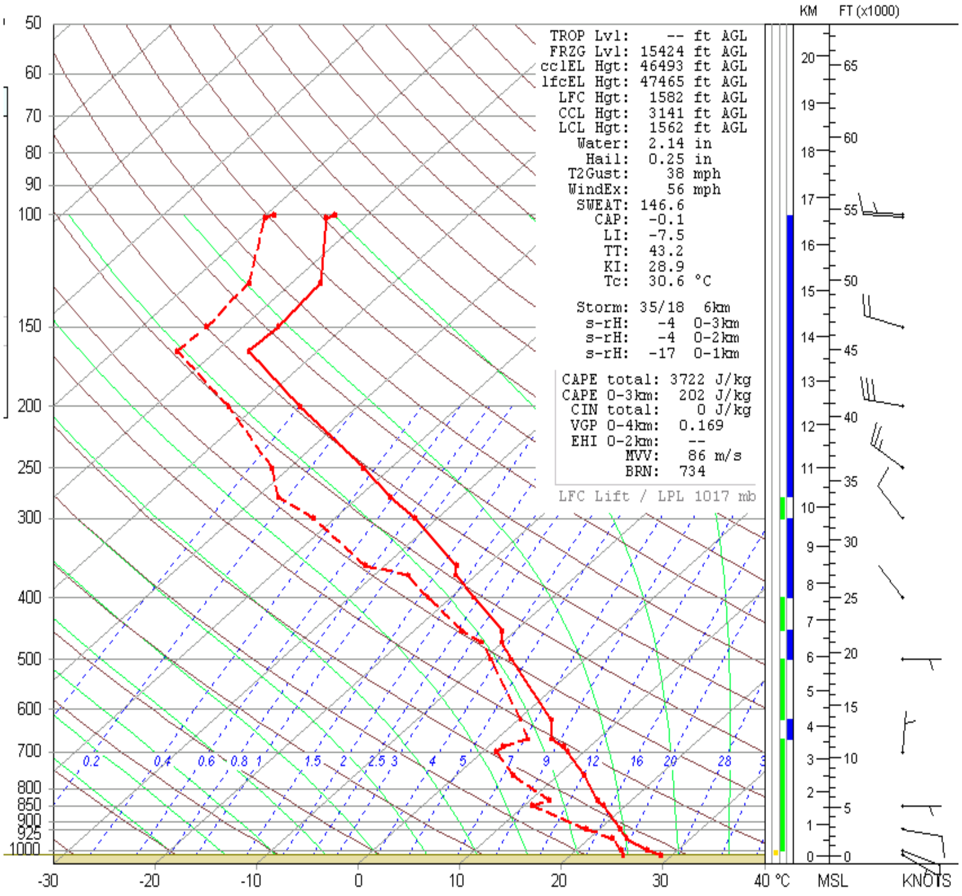


Figure 6. Skew-T Diagram, Key West 00Z 28 June 02

The thermal structure is characterized by a dry adiabatic lapse rate in the marine boundary layer below 950mb (545m) with moist adiabatic lapse rates above. A stable layer was noted between 670mb and 620mb. Moisture profiles for this sounding show a moist lower layer at the surface with substantial drying above 835mb (1700m). The Convective Available Potential Energy values were 3722 J/kg on the 28 June sounding with Lifted Index values of -7.5. The presence of the convectively unstable low levels and drying above the 835mb level fit well with the empirical criteria developed by Golden (1974). Wind profiles for the studied soundings show weak easterly winds in the lower levels backing to westerly above 300mb. In the stable layer the winds are easterly above and below with a northerly wind observed in the layer. Wind profiles for all soundings indicated low vertical wind shear, with –4 Storm Relative Helicity values on the 28 June 00Z sounding. This shear profile corresponds well with the empirical criteria developed by Golden (1974).

In summary the sounding data for Key West indicates an unstable thermal profile with low vertical wind shear. This type of sounding would be indicative of strong thunderstorms with a low potential for tornado development, based on the shear profiles.

D. BACKGROUND ENVIRONMENTAL SUMMARY

The analyzed data indicate the Key West Region was under the influence of a weak upper level ridge creating weak westerly winds aloft and very weak subsidence. In the lower levels the dominant feature was the subtropical high center over the eastern Atlantic Ocean generating weak easterly winds. The position of the low level ridge, relative to the storm, presents a pattern that is indicative of weak subsidence in the surface-700mb layer. The combination of low vertical wind shear and weak subsidence corresponds with Golden’s observations of synoptic environmental conditions favorable for waterspout development (Golden 1974). Additionally, the presence of intersecting boundaries and the position of the waterspout relative to the boundaries is a common characteristic noted by numerous studies as favorable for waterspout and Type II tornado development (Davis-Jones et. al. 2001, Simpson et. al. 1986).

III. ANALYSIS OF THE AIRCRAFT DATA

A. COLLECTION METHODS

The data to be analyzed were collected by the CIRPAS UV-18A Twin Otter aircraft (Fig. 7) on 27 June 2002 between 1715Z and 1856Z. The aircraft was on deployment to NAS Key West in support of the HALO II and Crystal-Face experiments. The purpose of the mission on 27 June was to investigate how cloud droplets form and grow upon condensation on aerosol particles (Jonsson 2005). The collection strategy was to find developing cumulus clouds, in their initial stages, and fly a series of legs below cloud base to determine the updraft velocities and characterize the aerosol particles. Then, traverse the cloud at incrementally increasing altitudes to characterize the evolution of the droplet population. On 27 June 2002 the aircraft deployed to collect data on developing cumulus clouds south of Key West. At approximately 1715Z the aircraft began surveying a cumulus cloud associated with a cloud line developing approximately in the North-South direction. The one cloud in the line chosen for the study was located approximately 15km south of Key West. It appeared more vigorous in its initial stages than the others.

Figure 8 depicts the flight patterns flown by the aircraft through the cloud under study. Fourteen passes were made below, in and above the cloud, as shown in the vertical depiction. During these passes the cloud grew, and by the time the flight pattern had brought the airplane to the top of the cloud it had reached an altitude of 3000m. The vertical depiction was plotted as longitude versus height, assuming constant latitude. The first leg was in the sub-cloud region and the fourteenth leg was flown just at cloud top, at approximately 3000m altitude. The aircraft flew a cloud relative pattern and data were collected at 1-second intervals. Following the cloud traverses, the aircraft conducted a spiral sounding in the environment immediately west of the cloud, from approximately 3000m down to 30m. At the end of the spiral the aircraft began another pass beneath the cloud, and then a waterspout was sighted extending from the cloud base. The leg was aborted. The mission scientist had noted during the flight, a cloud and turbulence free environment to the west of the cloud, while the eastern side exhibited significant turbulence and patchy clouds.

Figure 7. CIRPAS UV-18A Twin Otter

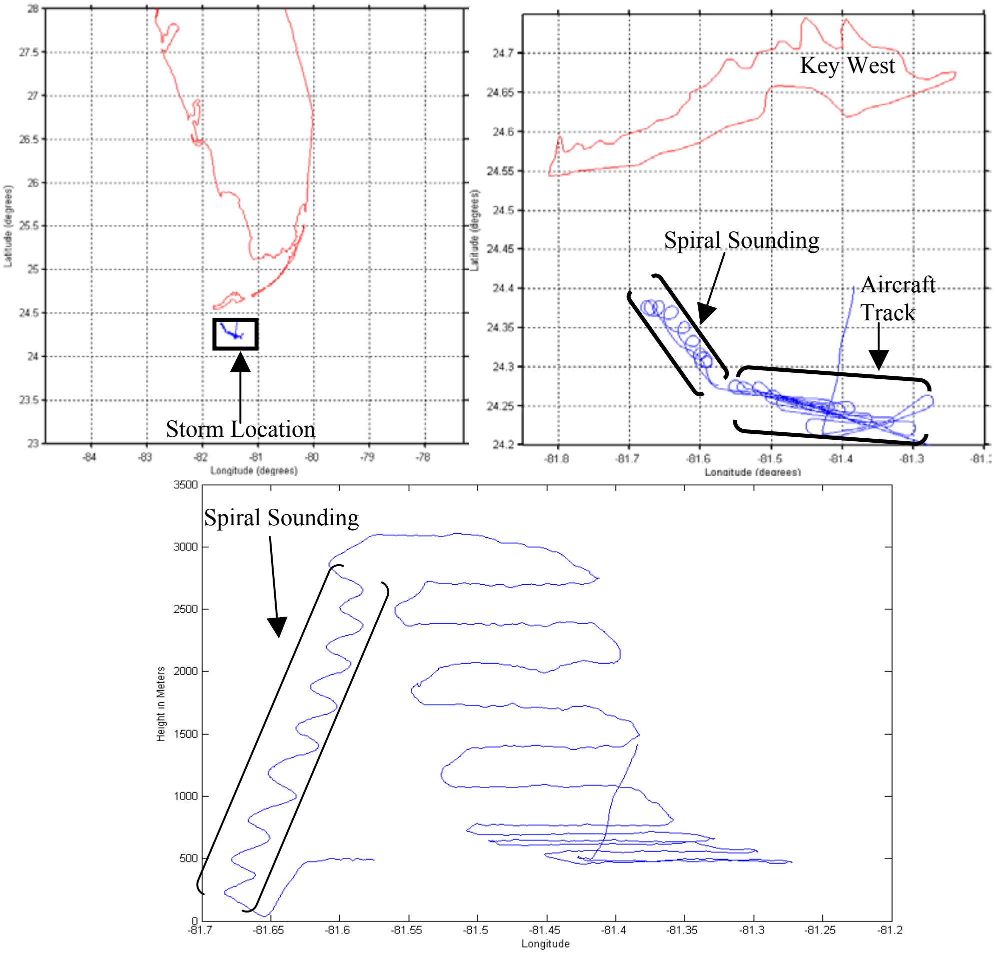


Figure 8. Plotted Flight path.

Upper left image is the larger scale image for reference to south Florida; Upper right image is a zoomed in view of the flight path relative to Key West. Lower Image is a plot of the vertical flight path.

Also, the updrafts and downdrafts associated with this cloud appeared more vigorous than in similar clouds probed nearby that day. The aircraft measurements verify these observations, and they also reveal a nearly 180-degree shift in the wind direction near the 850mb level, with southeasterly flow below and northwesterly flow above.

1. Payload

Table 1 lists the instrument package used on the Twin Otter during this experiment. The table format displays the element collected, manufacturer/model and measurement characteristics. Multiple sensors, for each element, were used to ensure data collection continued in the event that a sensor failure occurred. Items listed in red italics are the primary sensors for the analyzed data.

Instrument	**Manufacturer/Model**	**Measurement and Range**
Meteorology & Navigation		
Temperature	*Rosemount E102AL*	*Total Temperature -50C - 50C*
Temperature	Vaisala HMP 243	Total Temperature -50C - 50C
Dewpoint	*Edgetech 137-C3*	*Dew Point Temperature -50C - 50C*
Dewpoint	Vaisala HMP 243	Dew Point Temperature -50C - 50C
Static Pressure	Setra 270	1200 - 350 mb, 1100 - 600 mb
Flow angle - Radome	Radome (4 Setra 239)	0-30" H2O, -15-15" H2O
Flow angle -Wind	Rosemount 858 (6 Setra 239)	0-30" H2O, -15-15" H2O
NovAtel GPS	*NovAtel Communications Ltd.*	*Lat, Long, Alt, Grnd. Spd., Track, Vertical spd.*
TansVector Platform attitude	*Trimble*	*Pitch, Roll, Heading, Lat, Long, Alt*
C-Migets-II - INS/GPS	*Systron Donner Inertial Division*	*Position, Velocity, Attitude, Heading, Time,*
Radar Altimeter	*Collins ALT-50*	*Altitude: 0-500 ft (high resolution), 500 - 3000 ft (low res.)*
Aerosol & Cloud Physics		
PCASP	PMS, Inc., DMT Electronics	Size Dist: 0.1 mm < Dp < 3 mm
FSSP-100	PMS, Inc., DMT Electronics	Size Dist: 1 mm < Dp < 50 mm
CAPS	*DMT, Inc*	*Size Dist: 0.3mm < Dp < 50mm & 25mm < DP< 1400mm*
LWC (Part of CAPS)	*DMT Inc*	*0-1 g/Kg*
APS	TSI - 3320	Size Dist: 0.5mm < Dp < 30 mm
MOUDI	MSP Corporation	Collection of size classified Particles: 0.25 - 3 mm
Condensation Particle Counter	TSI - 3010	Dp > 10 nm
Condensation Particle Counter	TSI - 3010	Dp > 10 nm
Ultrafine Particle Counter	TSI - 3025	Dp > 3 nm
Twin Differential Mobility Analyzers	Caltech	Size dist 10 - 300 nm
Cloud Condensation Nuclei counter	Caltech	
Aerosol Mass Spectrometer	Aerodyne, Inc.	

Table 1. Twin Otter Aircraft Payload for HALO II Experiment.

2. Data Presentation Methods

The data presented in this section were plotted using the MATLAB program. All plots are distance versus height plots. Distance values on the x-axis were computed such that "0" is storm center. Cloud center points for each leg were calculated by determining the mid point of the leg between the cloud boundaries and distance was calculated from that point. Particle volume, or liquid water content and aircrew logs were used to determine cloud boundaries. Positive values are east and negative values are west. This shift was applied for presentation purposes, comparisons with height versus longitude plots revealed no significant discrepancies in feature locations. Wind vectors were plotted by decomposing the aircraft calculated winds into "u/v" components and applying a constant scale factor. Single element values; wind direction, wind speed, temperature, dew points, vertical velocities and equivalent potential temperature were plotted using a grid data method inside of MATLAB and applying a color fill routine. Plots were analyzed on two different scales; the first scale was 10km on a side to represent the environment around the cloud, the second was 1km on a side to provide detailed insight of the cloud. The cloud is primarily contained in the region within 500m of the center point.

B. DATA ANALYSIS

1. Horizontal Wind Field

For determination of horizontal winds, heading was obtained from the Trimble TansVector, a four antenna GPS system, true airspeed was calculated from the measured dynamic pressure and total temperature. Ground speed velocity and track were reported by the NovAtel GPS system (see table 1). Subtraction of the ground velocity vector from the true velocity vector then yielded the horizontal wind. Observations taken during aircraft maneuvering, typically at the end of the horizontal legs, were discarded due to dropouts and glitches in some of the GPS data. Figure 9 shows the computed horizontal wind vectors. Figures 10 and 11 show the wind directions and speeds respectively. As these figures show, the environment around the cloud was characterized by southeasterly winds, of about 5-7 m/s, below 1700m and northwesterly winds of about 4-5 m/s above. These winds are in general agreement with the winds observed on the Key West sounding. Around the 1700m in altitude the speeds are weak, or about 1-3m/s.

An anticyclonic shear zone thus prevails near the middle portions of the cloud. Figure 10 indicates downward mixing of the northwesterly winds aloft on the eastern side of the cloud where the aircraft log reported persistent turbulence.

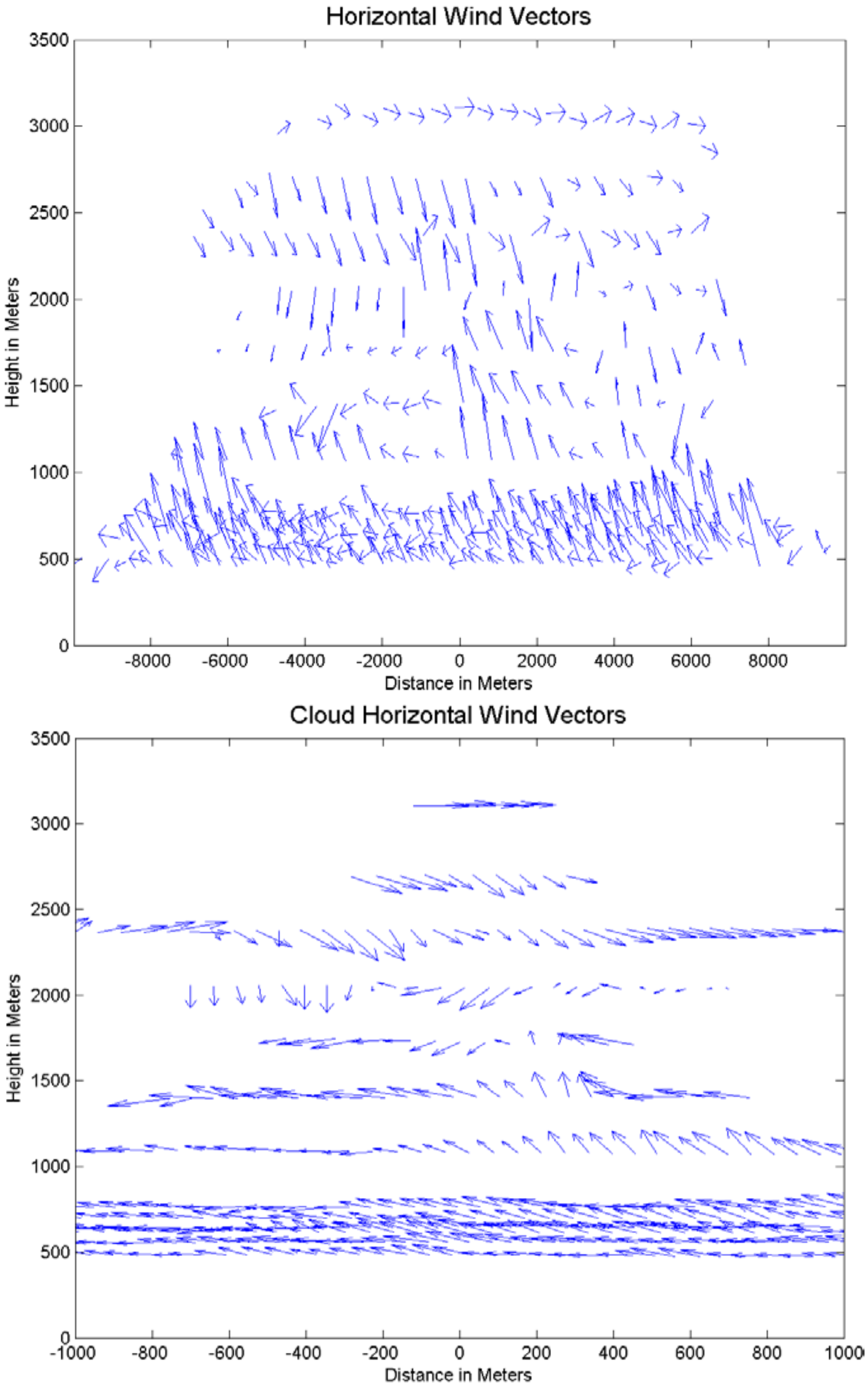


Figure 9. Horizontal Wind Vectors

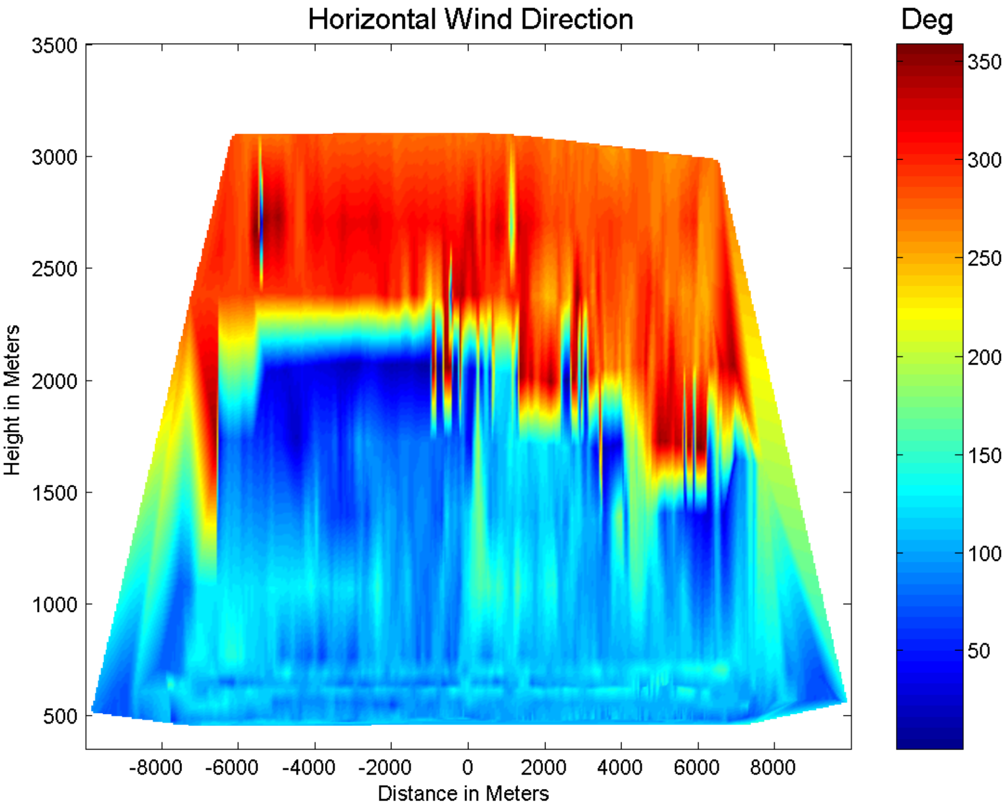


Figure 10. Horizontal Wind Direction

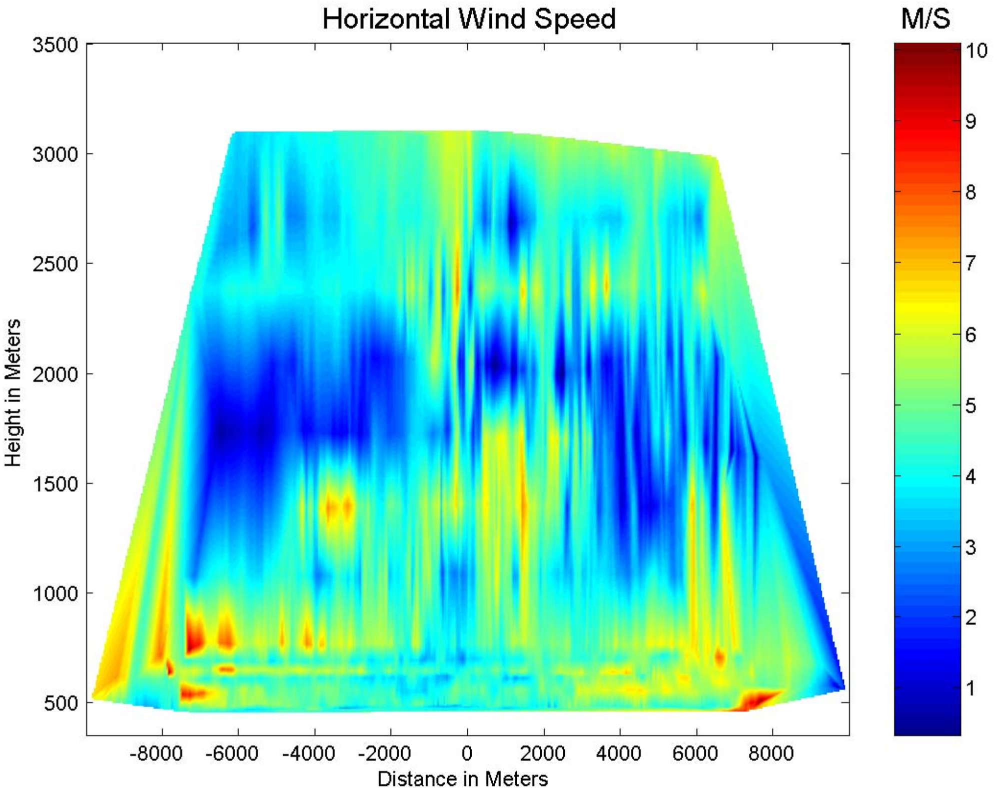


Figure 11. Horizontal Wind Speed

2. Temperatures

Ambient air temperature was obtained from measurements of total temperature using the Rosemount E102AL sensor, corrected for dynamic heating. Figure 12 depicts the ambient air temperature thus determined. The environment around the cloud depicts a reasonably uniform lapse rate on the western side of the cloud. On the eastern side, on the other hand, the figure exhibits a complicated thermal structure, consistent with the turbulence observations made by the scientist on the board the aircraft. In the mid levels of the cloud the turbulent mixing generated by the vertical wind shear has created a well-mixed layer. In the lower half of the cloud a temperature maximum is noted approximately 300m west of center extending vertically to 1700m. A temperature minimum is noted approximately 200m east of the cloud center extending from cloud top downward to 2200m.

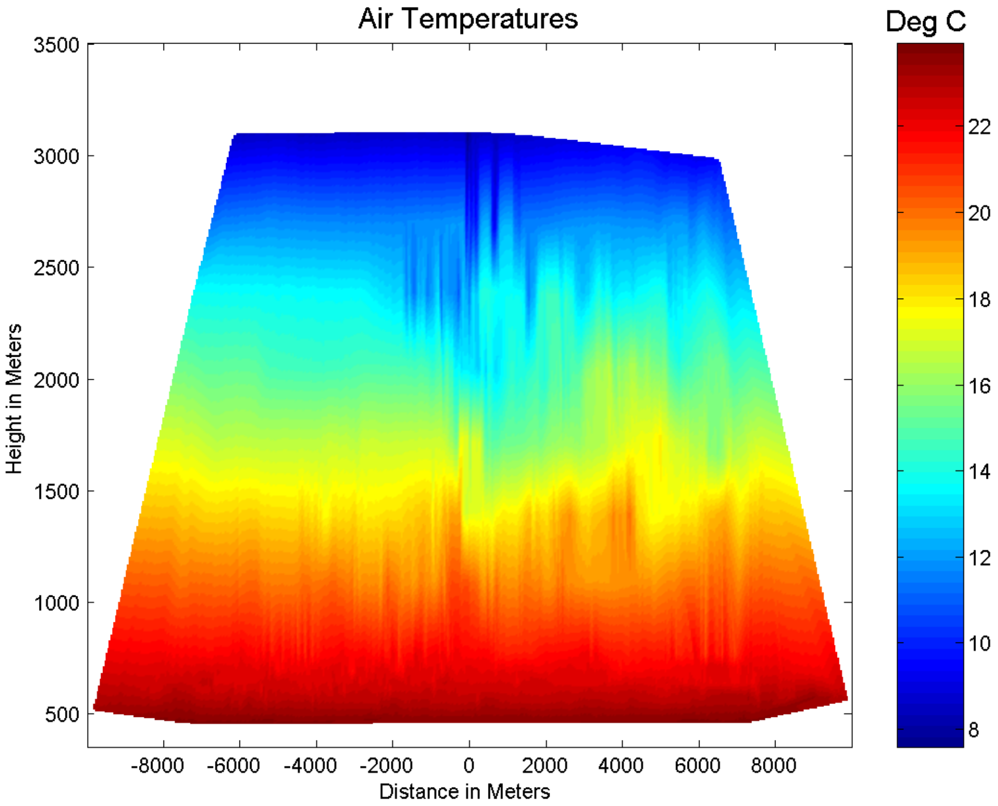


Figure 12. Ambient Air Temperature

3. Vertical Velocities

Vertical wind velocities were calculated using the flow angles measured at the radome, vertical speed reported by the NovAtel GPS system and pitch angle changes reported by the TansVector. Figure 13 depicts the vertical wind velocities thus determined. Vertical motions, of +/- 2 m/s, dominate the environment around the cloud. A prominent maximum in the upward velocities is evident, in the cloud, just west of its center with corresponding downward motions east of the center and elevated, maximum vertical velocities are approximately 8m/s. Closer examination of the cloud scale motions shows the strongest upward motions are between 1300m and 1600m approximately 200m west of cloud center. Maximum downward motions are between 1600m and 3000m approximately 400m east of the cloud center. The locations of the vertical velocity maxima correspond with the positions of the temperature extremes.

This structure most likely evolves as the cloud penetrates into the dryer air above 1700m. As the cloudy air mixes into the dry air and cools due to evaporation, it acquires negative buoyancy, while being carried eastward by the northwesterly flow at these levels. Thus the location of the resultant downdrafts appears east of the storm center. It is conceivable, although not clear from the data, that the descending air re-enters the southeasterly flow feeding into the cloud, forming a closed circulation.

Simpson et. al. (1986) modeled clouds from data collected on day 186 of the GATE experiment. Cloud F described in their research exhibits a vertical velocity structure very similar to the data collected for this study, with respect to locations of the vertical motion maxima; in their study cloud F spawned a waterspout. Waterspouts studied, in the Pacific Ocean, by airborne Doppler radar found that the clouds were typified by a strong updraft reaching a stable layer and overturning at the top (Verlinde 1997). This is a similar structure to the cloud under study. The upward motion extends vertically to the well-mixed layer, evident in the temperature plots, and then overturns at cloud top.

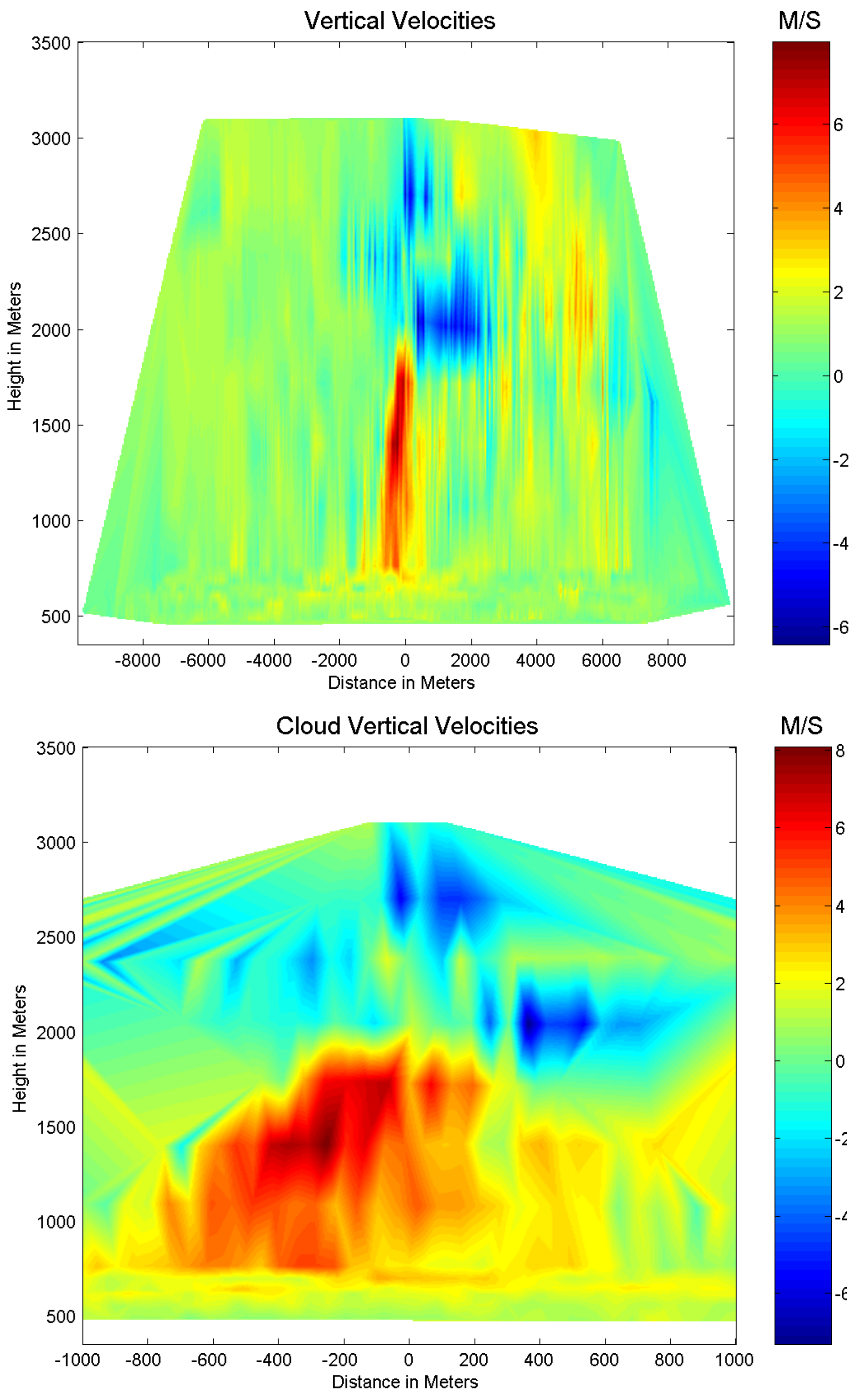


Figure 13. Vertical Velocity Fields

4. Dew Points

Dew point measurements were collected using the Edgetech 137-C3, chilled mirror sensor. A bit of caution must be exercised when using collected moisture variables. The sensor has a few second response time and therefore adjusts slowly to rapid changes in moisture content. The system also tends to over compensate when trying to reach an equilibrium state during periods of rapid changes in moisture content. This problem is most common at cloud boundaries. Given this issue the moisture variables will be analyzed realizing the limitations along the cloud boundaries. The dew point measurements in the environment exhibit a fairly uniform horizontal distribution with decreasing values with altitude, as expected. The most notable exception to this pattern is in the center of the cloud. A large spike in dew point values is evident approximately 300m west of the cloud center. This position correlates well with the location of the updraft maximum. This region is not on a cloud boundary so there is high confidence in the measured values. Closer examination of the dew point distribution internal to the cloud reveals a minimum in dew point values from cloud top down to approximately 2300m, located from storm center to 200m east. The location of this minimum corresponds to the region of maximum downdraft in the cloud.

5. Equivalent Potential Temperature

Equivalent potential temperatures (θe) values were calculated using the following equation:

$$\theta e = \theta * e \wedge \left[\frac{597.3 * S}{.24 * T} \right]$$

where θe = equivalent potential temperature, θ = potential temperature, S = saturation mixing ratio and T = ambient air temperature K^{o}. Figure 14 represents the θe calculations; caution must be exercised when interpreting the data since the calculated data depends on the measured moisture data. The most notable feature on the plots is the prominent maximum in values approximately 200m east of the center, with a vertical extent up to 2000m. The horizontal location coincides with the location of maximum vertical motion and the maximum in ambient air temperature.

The maximum has a greater vertical extent than both the vertical velocity and temperature maxima. The conservative nature of θe values permits the tracing of parcel motion through the cloud. The large values at the low levels along with elevated values in the downdraft regions east of the cloud center confirm the circulation hypothesis, presented in the discussion of vertical velocity patterns.

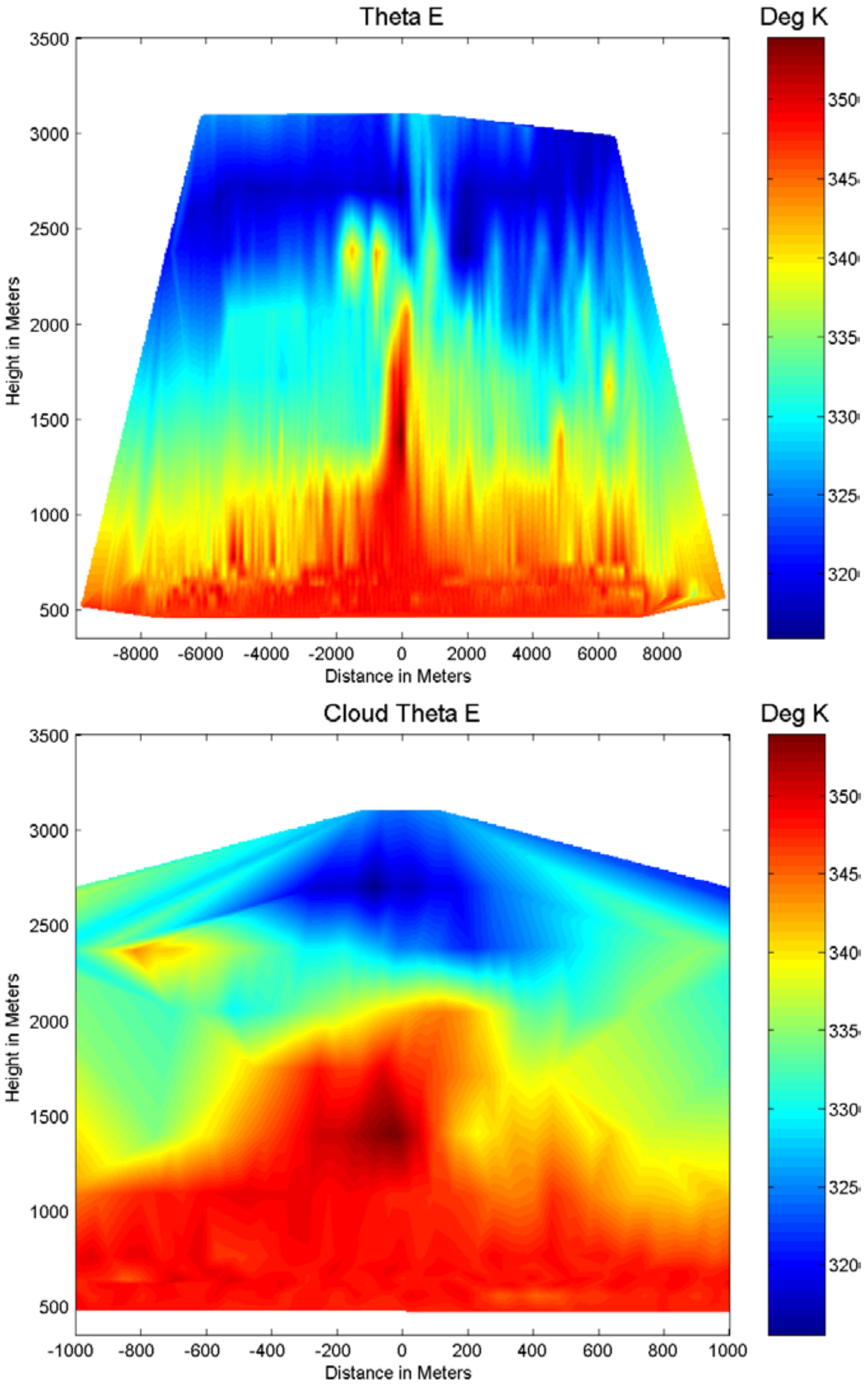


Figure 14. Theta E Values

6. Rotational Wind Plots

The data collected in this study were essentially collected in a 2 dimensional sense; aircraft flight patterns had very little latitudinal variance, and great longitudinal variance. This flight pattern creates a vertical cross section bisecting the cloud in an east-west fashion. The problem then arises, how to visualize 3 dimensional phenomena in a 2 dimensional view. Figure 15 represents the rotational component of the wind calculated using the east-west component of the horizontal wind as the "u" component and vertical velocity as the "v" component of the vector. The east-west component was chosen because it represents the largest magnitude of shear in the horizontal wind vectors shown in Figure 9. The resultant vector is one that displays the rotational wind when viewing the cloud from the south as an east-west cross section.

Figure 16 presents the rotation wind vectors overlaid with the observed vertical velocity field. The key feature in the figure is the circulation that appears in the cloud center. Of particular interest on this figure is the coincidence of the upward vertical velocity maximum with the ascending branch of the apparent vortex and the proximity of the downward maximum to its descending branch. The relationship between the vertical velocity maxima and a rolling vortex will be discussed further in Chapter IV.

7. Aircraft Sounding

The aircraft conducted a sounding, in the environment immediately west of the cloud. The sounding was conducting by a spiraling descent from approximately 3000m to 30m. Data were recorded at 1-second intervals. Figure 17 represents the sounding plotted using the collected data. The environment west of the cloud exhibits a dry adiabatic lapse rate in the sub cloud region with moist adiabatic lapse rates from cloud base to the top of the sounding. Substantial drying is noted above 750mb in the dew point profile. The winds are from the east at 10-20kts in the low levels with a sharp wind shift at approximately 1700m, above which the winds are from the west at 10-20kts. This wind profile fits the pattern noted in the horizontal wind discussion. Figure 18 presents the aircraft sounding overlaid with the Key West 00Z, 28 June 2002 sounding. The two soundings exhibit very similar thermal profiles. The primary difference is evident in the drying above 750mb on the aircraft sounding.

No convective indices were computed for the aircraft sounding due to the relatively shallow nature of the sounding. It would be expected that the indices are on the same order of magnitude as the Key West sounding due to the similar nature. Both soundings fit well with the empirical rules developed by Golden (1974).

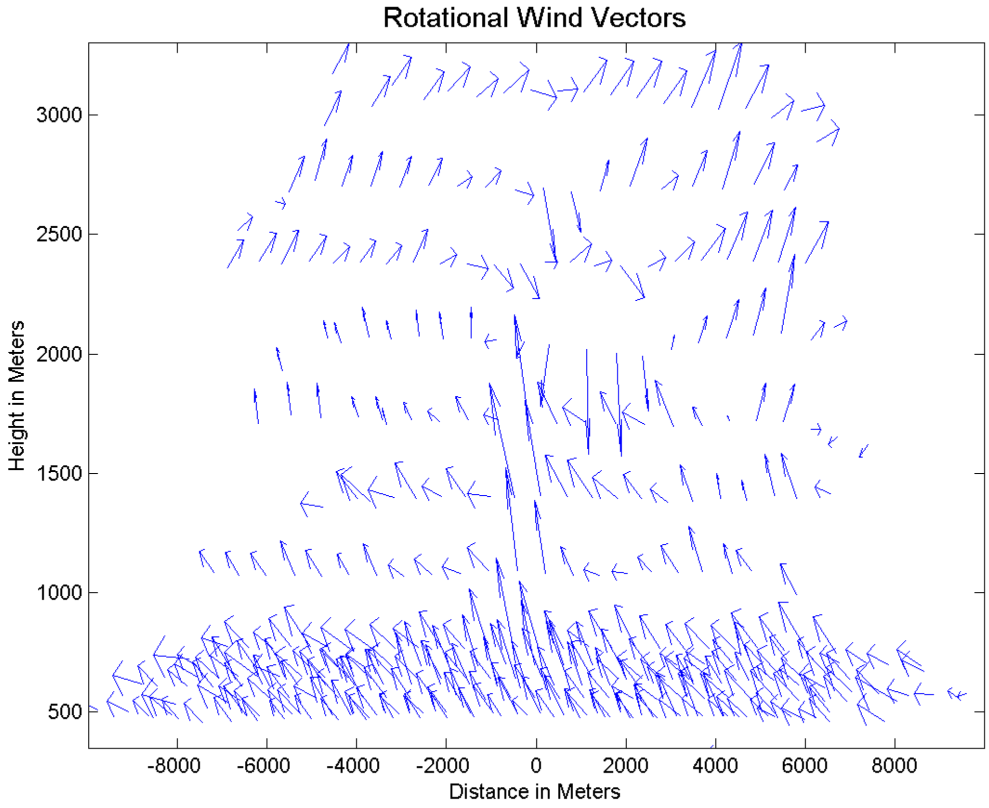


Figure 15. Rotational Wind Vectors

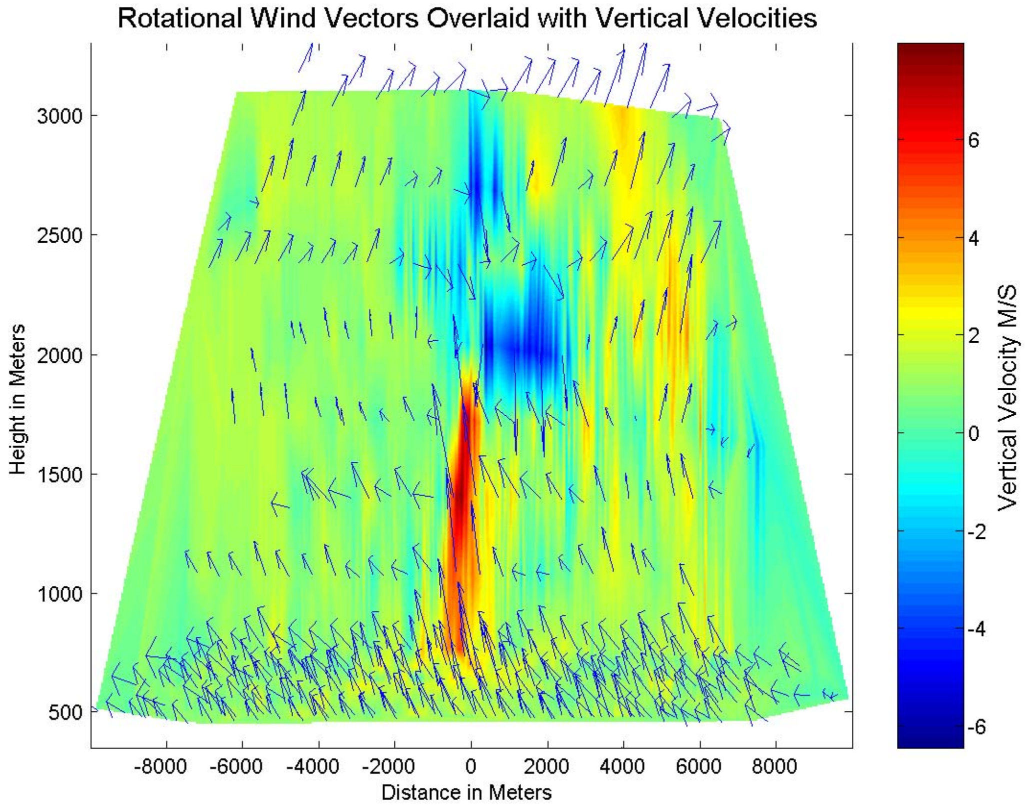


Figure 16. Rotational Wind Vectors Overlaid with Vertical Velocities

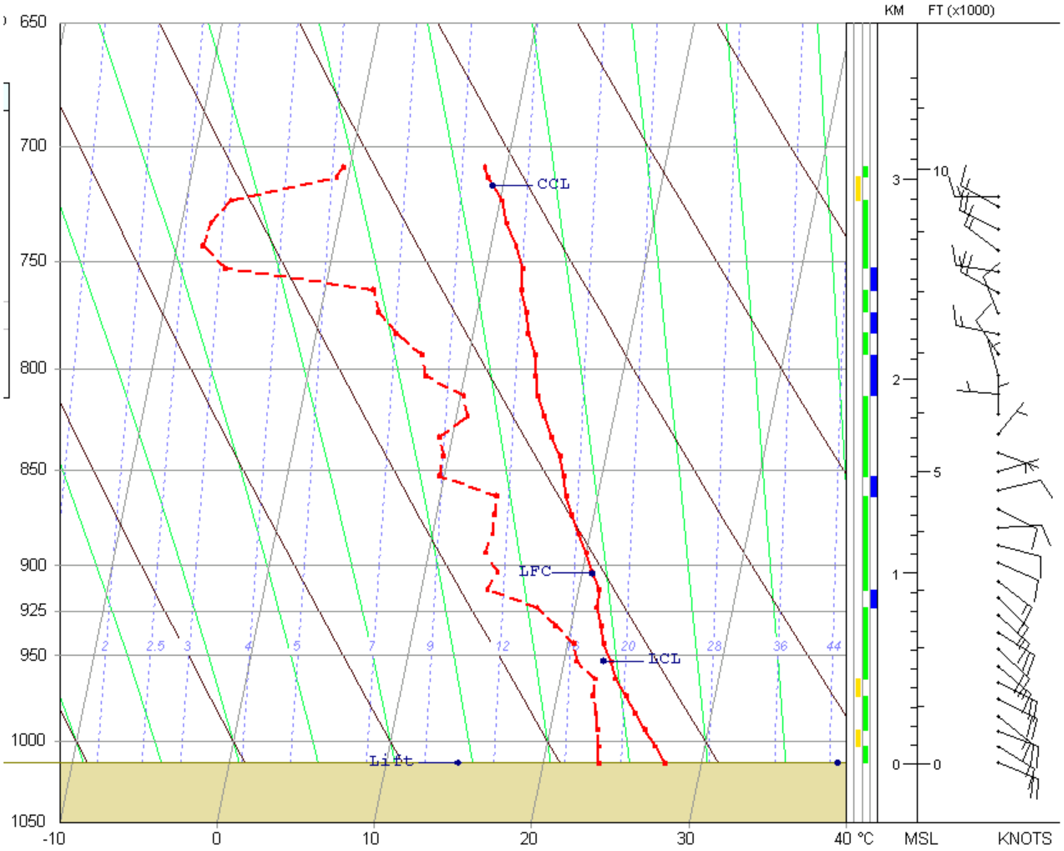
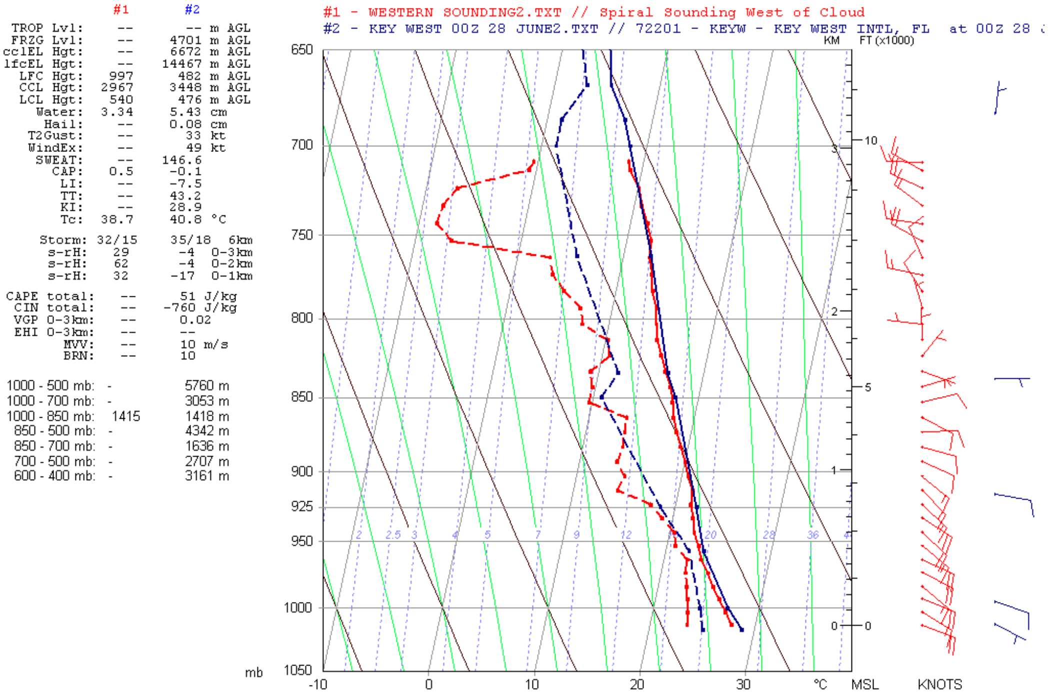


Figure 17. Aircraft Sounding West of Cloud



```
                 #1        #2
  TROP Lvl:      --        -- m AGL
  FRZG Lvl:      --      4701 m AGL
 cclEL Hgt:      --      6672 m AGL
 lfcEL Hgt:      --     14467 m AGL
   LFC Hgt:     997       482 m AGL
   CCL Hgt:    2967      3448 m AGL
   LCL Hgt:     540       476 m AGL
     Water:    3.34      5.43 cm
      Hail:      --      0.08 cm
   T2Gust:       --        33 kt
   WindEx:       --        49 kt
     SWEAT:      --     146.6
       CAP:     0.5      -0.1
        LI:      --      -7.5
        TT:      --      43.2
        KI:      --      28.9
        Tc:    38.7      40.8 °C

    Storm: 32/15     35/18   6km
     s-rH:   29        -4  0-3km
     s-rH:   62        -4  0-2km
     s-rH:   32       -17  0-1km

 CAPE total:    --       51 J/kg
  CIN total:    --     -760 J/kg
 VGP 0-3km:     --       0.02
 EHI 0-3km:     --       --
       MVV:     --       10 m/s
       BRN:     --       10

1000 - 500 mb:  -          5760 m
1000 - 700 mb:  -          3053 m
1000 - 850 mb:   1415      1418 m
 850 - 500 mb:  -          4342 m
 850 - 700 mb:  -          1636 m
 700 - 500 mb:  -          2707 m
 600 - 400 mb:  -          3161 m
```

Figure 18. Comparison of Aircraft Sounding to Key West Sounding 00Z 28 June 02. Aircraft Sounding in Red and Key West Sounding in Blue

THIS PAGE INTENTIONALLY LEFT BLANK

IV. DISCUSSION AND SUMMARY

A. DISCUSSION

Throughout his writings on waterspouts, Golden emphasized the importance of interaction between varying scales of phenomena and their effect on waterspout development. This research took the approach of looking at the cloud under study from a synoptic scale down to the microscale motions interior to the cloud. Each scale individually would not produce clouds capable of spawning waterspouts; it is the careful balance of interactions that creates an environment suitable for waterspout development. In their research during the GATE experiment, Simpson et. al. (1986) noted, "organized rotation in the form of vortex pairs is common in smaller, non-severe cumulus and may even be the rule when convective clouds develop upwards through ambient shear." The data presented through this study show that the studied cloud in fact developed vertically through an ambient shear environment. This in and of itself is not a rare occurrence in the region surrounding the Florida Keys, so why are the occurrence of waterspout funnels so relatively rare, when compared to the occurrence of this type of ambient shear? Simpson et. al. (1986) posed the question, what juxtaposition of mechanisms and ambient conditions are required to enable waterspout formation? The rest of this discussion will focus on summarizing the presented data and describing what the author feels was the necessary juxtaposition of phenomena, in this case, for the formation of this waterspout.

1. Synoptic Scale

On the synoptic scale, the key feature was the placement of the upper level short wave ridge relative to the low-level subtropical ridge. The short wave ridge was oriented in a manner to produce the west-northwest winds aloft. The ridge remained offset from the region of cloud development in a manner to produce the winds but not induce strong subsidence that, if present, would have acted to suppress convective development. The low-level subtropical ridge was oriented in a manner to produce the easterly low-level winds, thus generating the necessary background environmental flow and ambient shear for waterspout development.

2. Mesoscale

On the mesoscale, the key element was the placement of the two boundaries. The first boundary had origins in a sharp sea surface temperature gradient east of the cloud and propagated westward in the mean low-level flow. The parent cloud developed on this boundary producing the up and downdrafts in the horizontal shear zone necessary to generate an organized vortex. The second boundary was an outflow boundary propagating at a near right angle toward the first one from a large convective complex north of the Florida Keys. The resultant interaction of the two boundaries probably produced the tipping and stretching of the vortex that spun it up to form the waterspout. This hypothesis will be discussed in more detail in latter sections.

3. Cloud Scale

On the cloud scale, the key feature is the development of the cumulus cloud through the region of ambient shear. The cloud in question was one of many that developed along the convergent boundary propagating westward. Figure 16 suggests that the convective updraft in the cloud penetrates through the shear zone, and the compensating downdraft is shifted eastward by the shear, which are combined with the westerly flow above and easterly flow below to generate a rolling vortex. Heating due to condensation in the cloud drives the upward motion, while negative buoyancy due to penetration into dry air and evaporative cooling on the eastern cloud periphery drive the descending branch. Cloud parcels, associated with the vertical velocity maximum, rise through the shear layer, and due to entrainment of dry environmental air, evaporate, become negatively buoyant and begin descending. As the parcels lose vertical momentum they are displaced eastward by the upper level flow and begin descending east of the updraft core, accelerating as the cloud evaporates.

B. HYPOTHETICAL WATERSPOUT FORMATION PROCESS

This section will describe the hypothetical formation process of the waterspout in question. The theory behind this developmental process is derived from both the observed data and close examination of the sequence of events. Data will be rounded to even values for presentation purposes, but will remain within the same order of magnitude as the observed data.

Figure 19a represents the background environmental flow. Winds below 1700m are from the east at 10kts. A sharp wind shift is evident at 1700m, with winds from the west at 10kts above this level. This arrangement creates an anticyclonically sheared zone, as viewed from the south.

Figure 19b presents the plan view of the mesoscale situation. The key features on this image are the locations of the outflow boundary propagating southward and the convergent boundary propagating westward along the outflow boundary. The perpendicular intersection of the two boundaries is an important aspect of the arrangement. The cloud and subsequent waterspout were encountered near the intersection of these two boundaries.

Figure 19c shows the starting point for the developing cumulus cloud along the convergent boundary. The convergent boundary provides the lifting mechanism to begin the cumulus development. As the cumulus develops vertically, it is growing through the ambient shear present in the background flow. As the cloud develops, it eventually reaches a height sufficient to interact with the shear zone. This process is hypothesized by Simpson et. al. (1986) as a precursor for waterspout development.

Figure 19d represents a critical time in the waterspout formation process. This image illustrates a time in which the convective updraft has penetrated the shear zone aloft. As the updraft penetrates the zone, it gives a net vertical component to the parcels in the layer. Once the parcels begin to rise, they are cooled by adiabatic and evaporative processes and begin to lose vertical momentum. Loss of vertical momentum allows the parcel to be transported by the westerly wind. The now relatively cool parcel begins to descend east of the cloud. This process establishes the rolling vortex inside the cloud. Davies-Jones et. al. (1986) and Wilson et. al. (1992) hypothesized that type II tornadoes may form at the intersection of two wind shift boundaries and the ascending branches of boundary layer rolls. They noted the coincidence of vortex rolls and convective updrafts are established immediately since the convective initiation tends to be favored in the line roll intersections. In this case the penetration of the convective updraft through the sheared layer initiates a rolling vortex and creates an area of accelerated vertical velocities. An increase in the rotational speed of the rolling vortex in turn acts to accelerate the vertical motions. The upward motions are further enhanced by the thermal instability of the environment. Skew-t analysis indicates the notable thermal instability of the environment in which the cloud is developing. CAPE values are on the order of 3200 J/kg, indicating any parcel that is set into motion vertically will accelerate upward. Theta E analysis supports this theory; a large maximum in theta E is present near the maximum vertical velocities. A compensating increase in the descending branch of the rolling vortex must accompany the increase in the ascending branch. Evaporative cooling on the cloud boundaries further enhances the downward motions, thus the area of increased downward motions evident in the observed vertical velocity fields. Theta E values near the maximum downward motions were relatively high compared to the surrounding air. The conservative nature of theta E calculations would indicate the parcels originated in a region of increased theta E. This would suggest the air is being transported upward, undergoing evaporative cooling and descending, while retaining some characteristics of its origin.

Figure 19e again illustrates the plan view of the mesoscale situation. Prominent in this image is the proximity of the established rotating vortex to the outflow boundary propagating southward.

Figure 19f depicts a vertical cross section of the cloud as viewed from the west. The anticyclonically rotating vortex is established in the cumulus cloud. As the outflow boundary continues propagating southward, the upward motions ahead of the boundary begin interacting with the rolling vortex. This interaction serves as the tilting mechanism, acting to tilt the northern end of the vortex upward. The downward motions on the southern end of the cloud are established due to evaporative cooling, this sinking motion is an additive effect to tilt the southern end of the vortex downward.

Figure 19g depicts the vortex, now oriented vertically in the cloud. Figure 19h represents the fully developed waterspout extending from the base of the cumulus cloud. Differential vertical motions act to stretch the vortex and conservation of angular momentum intensifies the vortex, thus generating the funnel cloud.

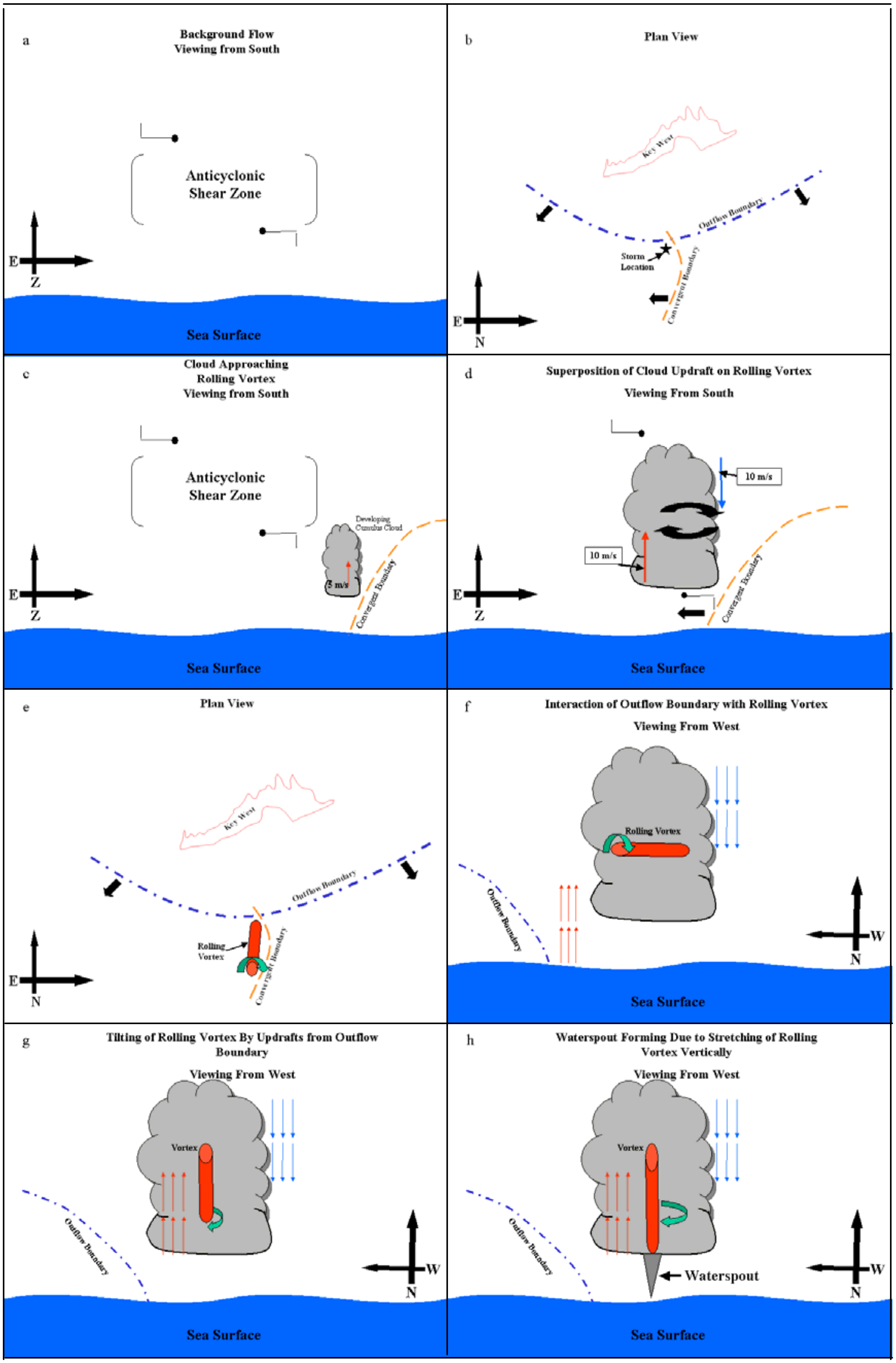


Figure 19. Hypothetical Waterspout Formation Process

C. SUMMARY

The lack of relevant observed data relating to waterspouts will continue to be the crux of the forecast problem. High-resolution data and model simulations must be developed to further understand the processes by which waterspouts form. This study has given first order treatment to, high temporal resolution, observed data in the parent cloud of a waterspout. This data has proven useful in verifying pervious studies, both modeled and theoretical, into waterspout development.

Analysis of the data from this study indicates that mechanical processes dominate the waterspout formation process and are enhanced by thermal processes. This ideology leads to the belief that the interaction of synoptic and mesoscale patterns are extremely important in the generation of waterspouts. The synoptic and mesoscale situation, in which the waterspout formed, fit within the bounds of empirical criteria developed by Golden (1974). The synoptic scale situation evolved in a manner that provided the appropriate mix of a light speed but highly directionally sheared wind environment. The placement of synoptic scale features provided the appropriate combination of weak subsidence and increased thermal instability, enabling the cloud to interact with the shear zone and establish the vertical velocity patterns necessary to form the rolling vortex. Findings of this study validate the vertical velocity patterns developed by Simpson et. al. (1986), while modeling clouds from day 186 of the GATE experiment. The placement of the convergent boundaries perpendicular to one another proved significant in the development process. The interaction of convergent boundaries and their role in type II tornadogenesis is a well-documented process and a key feature that can be readily identified by operational forecasters working in coastal regions. From this study some qualitative "rules of thumb" for identifying situations prone to waterspouts can be developed.

- A synoptic scale situation that provides weak wind speed shear but high directional shear, in the boundary layer.
- Strong thermal instability in the environment to allow convective development.
- Presence of mesoscale boundaries; outflow boundaries, convergent boundaries, gust fronts or weak low-level cyclonic features. The boundaries should be oriented perpendicular to one another, with one boundary parallel to the shear zone established by the wind flow.

While these rules of thumb are vague and qualitative, they do provide some guidance for forecasters working in coastal regions. Improving the forecasting process only slightly will lead to great advances in weather support provided to customers. Better forecasting schemes for waterspout formation will improve resource protection and operational planning for Department of Defense assets in coastal zones.

D. RECOMMENDATIONS FOR FUTURE WORK

The collection of relevant data on waterspouts is greatly needed to further the understanding of how they form. From this study, several ideas have arisen on how to collect this data. The first recommendation would be to deploy aircraft to regions like Key West during the summer months to collect the data. In this study the flight patterns were essentially 2 dimensional legs oriented east west. Future aircraft patterns should focus on attempting to collect data on cumulus clouds in a three dimensional sense. The legs should be oriented parallel to both convergent boundaries with numerous legs at increasing altitudes.

A second method for collecting data would be the use of MWR-05XP, mobile phased array radar, currently under development by CIRPAS, the NPS department of Electrical and Computer Engineering, and ProSensing, Inc. This radar possesses immense capabilities for collecting data in both high temporal and spatial resolutions. The utilization of this radar would provide much more data than the standard weather radars in use today due to the short life cycle and small spatial scale of waterspouts. An optimal scenario for collecting data would be the integration of the phased array radar and aircraft measurements. The radar would be placed at a strategic ground location, such as Key West, to interrogate developing cumulus. Radar operators could then direct the aircraft to clouds that show early signatures of waterspout development. The radar operator could also provide optimal altitudes for the aircraft to fly in order to capture microscale phenomena such as the rolling vortex in a cloud. Doviak et. al. (2001) noted that it is possible to interleave a sequence of beam positions so that weather characteristics along a path of an object such as aircraft can be obtained with radar and in-situ instruments. This would allow for comparisons of in-situ aircraft observations and radar measurements (Doviak et. al. 2001).

THIS PAGE INTENTIONALLY LEFT BLANK

LIST OF REFERENCES

Davies-Jones, R., Trapp, R.J., and Bluestein, H.B., 2001: Tornadoes and Tornadic Storms, *Severe Convective Storms, Meteor. Monogr.*, Vol. 28, No. 50, Amer. Meteor. Soc., 167-221.

Doviak, R.J., D. S. Zrnic, and A. Shapiro, 2001: Phased array weather radar-benefits and challenges. Preprints, *30th International Conf. on Radar Meteorology*, Munich, GE, Amer. Meteor. Soc., 202-204.

Golden, J. H., 1974: Life Cycle of Florida Keys' Waterspouts. NOAA Tech. Memo ERL NSSL-70, 147pp.

Jonsson, H., 2005: Personal Communication Reference HALO-II Experiment, Chief Scientist, Center for Interdisciplinary Remotely-Piloted Aircraft Studies, Naval Postgraduate School, February 2005.

Simpson, J., Morton, B.R., McCumber, M.C., Penc, R.S., 1986: Observations and Mechanisms of GATE Waterspouts. *J. Atmos. Sci.*, **43**: 753-783

Verlinde, J., 1997: Airborne Doppler Analysis of a Waterspout. *Mon. Wea. Rev.***,** **125**, Iss. 11, 3008-3018.

Wilson, J.W., Foote, G.B., Crook, N.A., Frankhauser, J.C., Wade, C.G., Tuttle, J.D., and Mueller, D.K., 1992: The role of boundary-layer convergence zones and horizontal rolls in the initiation of thunderstorms: A case study. *Mon. Wea. Rev.,* **120**, 1785-1815.

THIS PAGE INTENTIONALLY LEFT BLANK

INITIAL DISTRIBUTION LIST

1. Defense Technical Information Center
   Ft. Belvoir, Virginia

2. Dudley Knox Library
   Naval Postgraduate School
   Monterey, California

3. 45th Weather Squadron
   Patrick AFB, Florida

4. 46th Weather Squadron
   Eglin AFB, Florida

5. Dr. Keith Blackwell
   University of South Alabama
   Mobile, Alabama

6. Dr Joseph Golden
   National Oceanic and Atmospheric Association
   Boulder, Colorado

7. Professor Wendell Nuss
   Naval Postgraduate School
   Monterey, California

8. Haflidi Jonsson
   Cooperative Institute for Remotely Piloted Aircraft
   Monterey, California