Kinematic Analysis of Hurricane Isabel at Landfall

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Abstract

A unique dual-Doppler data set of the landfall of Hurricane Isabel was analyzed. These data were collected with the Shared Mobile Atmospheric Research and Teaching (SMART) radars that were deployed in North Carolina along a 54 km north-south baseline. The radars collected more than 14 hours of coordinated dual-Doppler scans during the landfall of this category two hurricane, including the passage of the eye-wall that went through the dual-Doppler lobe. High spatial resolution volumes were collected every 2-4 minutes providing exceptional temporal resolution.

This study focused on the mesoscale evolution of several of the rainbands during landfall. In particular, variability in precipitation was related to kinematics of the airflow through the forward right flank of the hurricane as the rainbands made landfall. The variability of precipitation at different temporal and spatial scales during hurricane landfalls is a particularly relevant issue for the student-led test-bed being deployed in Puerto Rico. This study also has implications to the Houston, TX test-bed that will focus on hydrological applications.

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1. Introduction

a. History

Shortcomings in the current understanding of hurricane dynamics are responsible for errors in forecasting hurricane landfall, which results in additional errors forecasting the location and amount of heaviest precipitation. In the last five years, there has been an emphasis on the study of the small-scale dynamics of hurricanes to improve the forecasting of inland flooding (Elsberry 2002). As part of the effort to improve the forecasting of hurricanes, the Hurricane Research Division (HRD), under the National Oceanic and Atmospheric Administration (NOAA), conducted a hurricane field program in 2003 (Dodge et al. 2003). The main goal of this field project was to improve the forecasting of hurricane track and changes in storm intensity in addition to expanding the current understanding of the behavior and structure of hurricanes. One of the objectives of this field program was the study of tropical cyclone wind fields near landfall. As part of that study, flight data from the NOAA WP-3D and ground-based WSR-88D radars were used by the National Hurricane Center /Tropical Prediction Center (NHC/TPC) in their real-time and post-storm analysis of hurricanes during the field program. One of the conclusions of that project emphasized the need for mobile radars to collect dual-Doppler data sets within twenty-four hours of the hurricane reaching land.

Most of the understanding of hurricanes can be attributed to measurements from airborne Doppler radar, buoy systems, and satellites. In the past, airborne radar had limitations on time continuity since the aircraft had to adjust its flight path to send out intersecting radar beams by flying two separate legs. Aircraft radar coverage was not as simultaneous as with ground-based mobile radars, resulting in a time lapse that prevented resolving convection-scale motions over the radar analysis domain. Airborne radars also have size and weight limitations that require the size of the antenna to be small and force the use of attenuating wavelengths. As a result, the beam width and attenuation increases with range creating difficulties interpreting data at farther distances (Barnes et al. 1983). The aircraft also is not stationary, which can result in aircraft motion biasing velocity measurements and can produce non-uniform resolution because the sample volume continually changes.

Ground-based dual-Doppler analysis can be more detailed and, perhaps more, accurate than aircraft-based analyses. Ground-based dual-Doppler radars can sample a large volume of space more rapidly than a single aircraft, minimizing the effort of evolution on wind retrievals. Ground-based mobile radars can also detect features at lower levels of the atmosphere better than aircraft-based radars. Aircraft radar beams have problems at lower levels when the beams intersect the ground creating backscatter that masks real precipitation (Biggerstaff et al. 2005). In addition, past aircraft observations were only able to resolve large-scale features, but ground-based dual-Doppler radars can detect smaller scale features within individual rainbands. The ability to detect small scale features in the lowest levels is key to improving the rainfall estimates of inland flooding.

b. Conceptual Model

The conceptual model (Fig. 1; from Marks and Houze 1987) of a vertical cross-section through a hurricane shows the airflow and precipitation structure of an inner rainband. Their model (referred to hereafter as the MH conceptual model) was derived from a series of aircraft observations. At location 4 in Fig. 1, low-level inflow into the hurricane feeds the eyewall convection located within the darkest shaded area at locations 1' and 2'. This is the area of the strongest convergence and divergence. As air travels into this region of convergence it is forced to travel upward due to the conservation of mass. Air parcels cool as they rise, which causes condensation that allows precipitation particles to grow and the formation of ice above the freezing level (dotted line from locations 0-1). The particles continue to grow by vapor deposition and aggregation until they are too large to be maintained by the updraft. When this occurs, the particles begin falling towards the ground, undergoing phase change from ice to liquid (location 3). The radar senses partially melted ice particles as rain large drops leading to a pronounced region of reflectivity near the melting level (location 3). The melting of the ice results in a stratiform inner rainband down windfrom the convective eyewall. The conceptual model suggests the stratiform rain region has both a mesoscale updraft and a mesoscale downdraft separated at the melting level. These mesoscale vertical drafts resemble those observed in tropical squall lines in at least two ways: they emanate approximately from 0º C, and they have average magnitudes on the order of 10 cm s^{-1}. Marks and Houze (1987) follow Leary and Houze (1979) and Gamache and Houze (1972) by indicating that the mesoscale downdraft in the hurricane was likely initiated by the melting of hydrometers.

c. Objectives

The goal of this project is to document the relationship between the reflectivity field and the evolution of wind flow through a land-falling hurricane rainband. One of the objectives is to compare our results with the MH conceptual model. This project focuses on the kinematics of Hurricane Isabel in 2003. The data were collected from two SMART (Shared Mobile Atmospheric Research and Teaching; Biggerstaff et al. 2005)

Doppler radars deployed to intercept this land falling hurricane. Major steps in achieving the goal of this study included editing the raw radar data, converting from polar to Cartesian coordinates, and retrieving the three-dimensional wind fields. The key here was to analyze the reflectivity and wind fields to determine how well this case-study fits the conceptual model of Marks and Houze (1987).

2. Data and Methodology

a. Data collected

Hurricane Isabel came ashore near Drum Inlet on the Outer Banks of North Carolina on 18 September 2003. Isabel was a classic Cape Verde tropical cyclone that originated as a westerly wave on 1 September 2003 off the western coast of Africa (Figure 2). Although Isabel at one time was a Category 5 hurricane according to the Saffir-Simpson scale, it made landfall as a Category 2 according to the National Hurricane Center (Beven and Cobb 2004). The data used in this project were taken from the two SMART-Rs deployed along a 54 km baseline oriented north to south. SMART-R1 (SR-1) was stationed at Washington, North Carolina, and SMART-2 (SR-2) was located at New Bern, North Carolina (Fig. 3). The dual-Doppler lobes (hatched regions in Fig. 3) were located to the east and west of the radars. The lobes indicate an optimal area in which the Doppler data from the two radars can be used to retrieve the three-dimensional wind. For this project, only data from the eastern dual-Doppler lobe was used because the hurricane came ashore from that direction.

The data used here are from the Characterization of Atmospheric Turbulence and Flood Initiation and Verification Experiment (CAT -FIVE) that produced the first mobile C-band dual-Doppler observations of a land-falling hurricane. The coordinated radar data between the two SMART-Rs began around 0930 UTC and ended around 2200 UTC on 18 September 2003, yielding observations of the inner rainbands and eyewall of Hurricane Isabel as it made landfall. The objective of CAT-FIVE included both mesoscale and convective scale processes. Both radars repeated a pre-determined sequence of scans on a 40-minute cycle with two 20-minute blocks of time. The first 20 minute-block was dedicated to mesoscale processes. This study makes use of the mesoscale processes data set that contains both full 360º volume scans and 130º sector scans at several elevation tilts (Table 1). The 130º sector scans required two minutes to complete while the full 360º volume scan required four and a half minutes. Here, we analyzed several volume scans between 10:44:30 UTC to 12:43:40 UTC (Table 2) when the inner rainbands were making landfall.

b. *Methodology*

1) DATA EDITING

The SOLOii editing software (Oye et al. 1995) was used to edit the raw data from SR-1 and SR-2. Six out of the ten volume scans were edited manually. The rest were edited automatically, using a utility developed by C. Alexander. The main steps were dealiasing velocity measurements and deleting noise and second-trip echo. Dealiasing was necessary because the wind speeds in the hurricane exceeded the ±20 m s^{-1} Nyquist velocity of the radars. At low tilts, some of the radar beams experienced blockage by trees and redirection by nearby metallic buildings. Rays that appeared randomly redirected were deleted from the dataset.

2) INTERPOLATION

The edited data were interpolated to Cartesian coordinates using the REORDER program (Oye et al. 1995). The Cressman weighting interpolation method with a beamwidth dependent radius of influence was used. The radius of influence varied with range such that high resolution in the region closest to the radar was retained while low resolution occurred in regions farther from the radar (Fig. 4). The dimensions of the analysis grid extend from 0 to 100 km in the x (east-west) direction, from -40 to 94 km in the y (north-south) direction, and from 0 to 11 km in the z (vertical) direction with SR-2 being the origin of the coordinate system. The horizontal spacing between points is 1 km and the vertical spacing is 0.5 km.

3) WIND RETRIEVAL

REORDER output for the two radars were combined and used to retrieve the three-dimensional wind fields using CEDRIC (Custom Editing and Display of Reduced Information in Cartesian Space; Mohr et al. 1986). Our analysis takes into account the radar reflectivity-based estimated fall speed of the participation particles following the procedure outlined in Biggerstaff and Houze (1991). A two-step Leise (1981) filter was applied to the horizontal wind components before computing divergence. This led to a resolvable horizontal scale of around 6 km. The resolvable vertical scale, determined by the elevation tilts of the volume scans, was ~2-4 km depending on the range from the radar.

The divergence field was integrated downward using a fraction of the integrand as a boundary condition to retrieve vertical motion. The horizontal winds were corrected for the vertical motion, and the flow field recomputed iteratively until the solution of the winds converged. Only 2-3 iterations were necessary for the solution to converge.

3. Results

a. Example of an individual analysis

To illustrate the airflow resolved by the dual-Doppler analysis, Fig. 5 shows the reflectivity and vertical velocity fields at 6 km altitude from the 1045 UTC analysis.

Ground-relative wind fields were superimposed in both panels. At this time, the 6 km altitude horizontal structure consisted to two primary branches. One branch was directed from east to west across the northern two-thirds of the analysis domain. The other branch was directed towards the southwest and appeared to be associated with the highest reflectivity part of the rainband. At lower altitudes, the entire flow field became more curved towards the southwest— an indication of flow around the low-pressure center of the hurricane.

At 6 km, vertical motion in the east-to-west flow was predominantly downward while in the southwestward flow the mean vertical motion was upward. Indeed, the lowest reflectivity part of the precipitation field at this level was affected by mean downward vertical motion that would have further deteriorated the hydrometeors through sublimation and evaporation. In contrast, the high reflectivity region was dominated by upward motion that would likely increase hydrometeor mass through vapor deposition.

The variability in vertical motion, observed throughout the cloud layer, likely affected surface rainfall patterns (Fig. 6). However, the accumulated rainfall was a net effect of numerous rainbands traversing the coast. It is beyond the scope of this study to determine the impact of one single rainband on the total observed rainfall. Hence, we can only hypothesize that the mesoscale variability in vertical motions observed here contributed to the variation in surface rainfall.

b. Summary of rainband structure

The original goal of this project was to compare the mesoscale features of a land-falling hurricane to those of the MH conceptual model. Here we emphasize the structure of the mesoscale vertical drafts in the stratiform rainbands. The MH conceptual model (Fig. 7a) shows that mesoscale updrafts and downdrafts are approximately equal in magnitude. Moreover, the mesoscale updraft and downdraft are separated by the melting level. As suggested by Leary and Houze (1979), the cooling from melting of hydrometeors at the 0°C level is a primary mechanism for driving the mesoscale downdraft. The mesoscale updraft, on the other hand, is likely associated with the remaining buoyancy from the air flowing outward from the eyewall convection.

Contrary to the MH conceptual model, the structure of the mesoscale vertical drafts in Isabel at landfall were not separated by the melting level. Additionally, the vertical drafts were significantly different in magnitude. The analyses indicate a weak updraft above the melting level and a more pronounced updraft between the melting level and 1 km. Relatively weak downward motion existed below 1 km.

One factor that could explain the discrepancy between the conceptual model and our results is that the conceptual model is likely based on observations through the strongest part of rainbands while our analysis includes the entire dual-Doppler domain, which contains the weaker precipitation regions as well. It was already noted that considerable variability in the strength of the mesoscale updraft existed across the weak and strong reflectivity portions of the rainband. This likely reduced the strength of the mean upward motion above the melting level.

Another important factor that likely affected the diagnosed circulations within Isabel is that a warm front was near the North Carolina coast prior to landfall. Indeed, the SMART radar operators noted that they were originally on the cool side of the frontal zone. As the hurricane pushed inland, the frontal zone retreated westward. The low-level mean upward motion diagnosed from the dual-Doppler analysis is probably a reflection of air flowing over the frontal zone. Hence, the air was forced upward even though it was subjected to cooling by melting and evaporation.

Given the proximity of the landfall to the frontal zone, it is difficult to gauge whether or not interactions with the land itself altered the mesoscale vertical motions within the rainbands. That question is left to future studies.

c. Comparison to numerically simulated hurricanes

Even though access to a simulation of Hurricane Isabel was not available, the magnitudes and variability of vertical motion retrieved from the dual-Doppler analysis still could be compared to simulations of similar hurricanes. This is needed because, to the authors' knowledge, no other ground-based dual-Doppler wind fields of a land falling hurricane have been published. Hence, other than aircraft observations taken within hurricanes (e.g. Jorgensen 1984; Jorgensen et al. 1985), there is a lack of knowledge on the strengths and spatial distribution of vertical motions within these storms.

From the dual-Doppler analysis, there are convective-scale features that have not been well documented previously. At lower levels, there is evidence of boundary layer rolls and hexagonal convective cells (Fig. 8) while at upper levels some convective scale vertical drafts are found within the otherwise stratiform rainband (compare to Fig. 5). The ability to diagnose and understand the importance of these finer scale vertical drafts on the overall precipitation production within the rainbands will help further studies in the area of inland flooding.

As an initial step towards confirming that the diagnosed convective-scale vertical velocities are reasonable, a comparison is made with a numerical simulation of Hurricane Charlie (Fig. 9; provided courtesy of L. Leslie and A. Fierro). The maximum upward motions from their simulation are greater than 4 m s^{-1}; and the maximum downward motion was around -2 m s^{-1}. For our case, the maximum values from the dual-Doppler analysis of the rainbands within Isabel were around 5 m s^{-1}, while the downdraft values were also around -5 m s^{-1}. The fact that the magnitudes are comparable provides some degree of confidance in that the dual-Doppler retrieval appears reasonable. It is also interesting to note that the simulation of Hurricane Charlie shows some convective drafts embedded in the otherwise stratiform inner rainband region. Similar convective features were observed in Hurricane Isabel.

4. Summary and Future Work

The consistency of the vertical velocities with simulations of hurricanes offers optimism for the future use of dual-Doppler ground-based mobile radars. The ability to diagnose convective scale features over broad regions during hurricane landfall is unprecedented. This will help in understanding the interaction between the wind and precipitation fields and aid in validation of numerical models.

Validation efforts tend to focus on properties related to the integrated effects of microphysical and storm dynamic interactions ignoring the details for lack of observational data against which to compare. With these analyses, more sophisticated validation with stronger constraints can be attempted. Hopefully, that will provide much needed guidance to modeling studies of hurricanes that, in turn, will lead to better forecasts of floods from land-falling tropical cyclones and a reduction in the loss of life from inland flooding.

Acknowledgments

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Table 1. Elevation angles used by the SMART radars during Hurricane Isabel. Parenthesis ( ) indicate elevation angle of SR-2 if different from SR-1. SR-2 did not collect the 32.7 degree tilt during the 130° sector scan.

130° Sector scan	360° Volume scan
1.0 (0.8)	1.0 (0.8)
1.5	1.5
2.3	2.3
3.2	3.2
4.3	4.3
5.4	5.4
6.9	6.8
8.7	8.4
10.8	10.2
13.2	12.2
15.9	14.5
18.9	17.1
22.2	20.2
25.7	23.2
29.2	26.9
32.7	30.5
	34.6

Table 2. Starting times of the volume scans analyzed here.

Time (UTC)
10:44:30
10:47:00
10:49:30
10:52:00
10:56:30
11:29:30
11:32:00
11:36:30
12:00:00
12:04:30

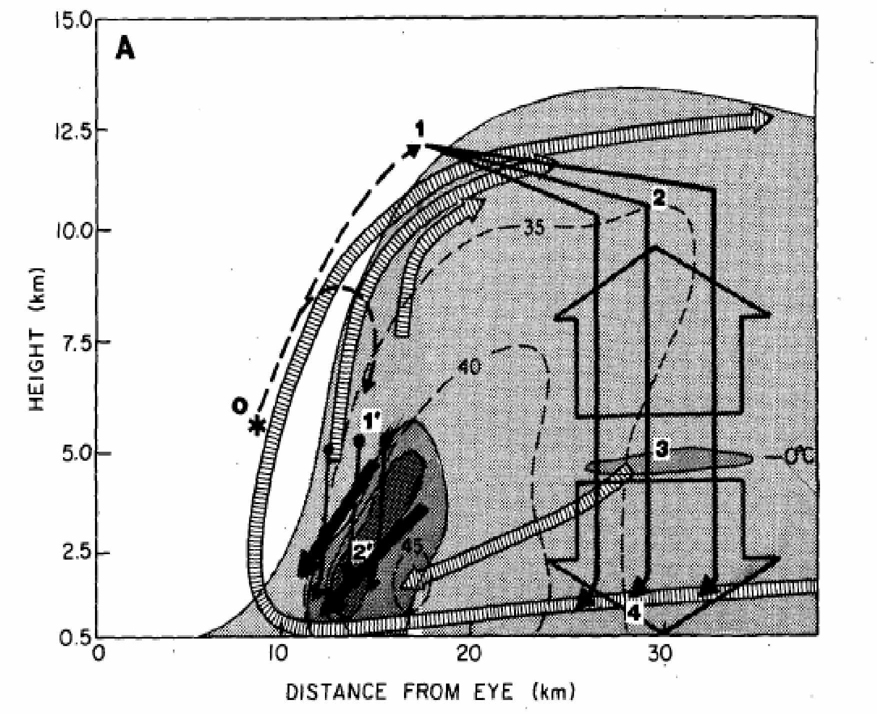


Figure 1. Aircraft conceptual model of a vertical cross-section of an inner rainband, from Marks and Houze (1987).

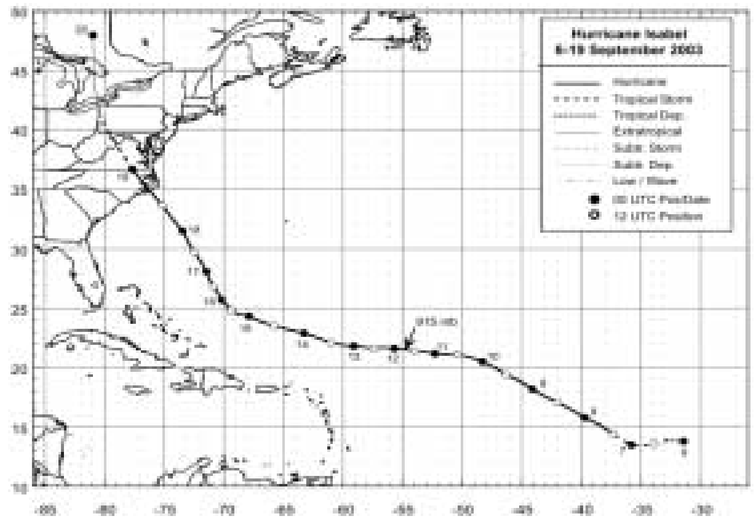


Figure 2. Best track positions for Hurricane Isabel, 6-19 September 2003, from the National Hurricane Center.

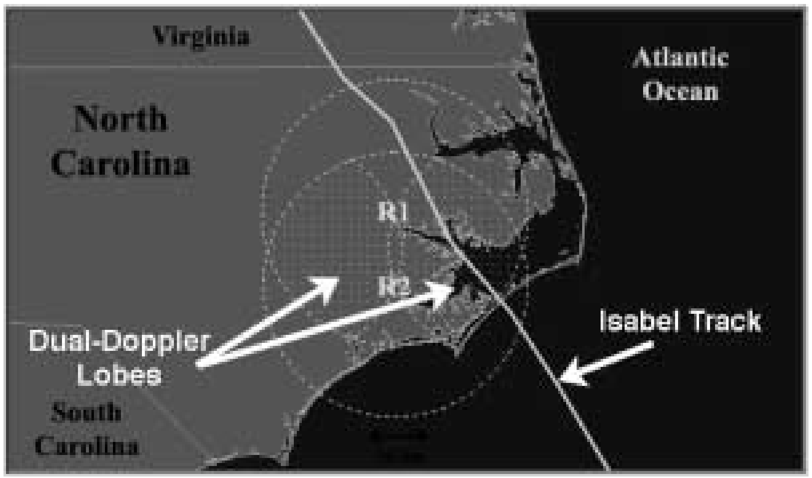


Figure 3. Track of Hurricane Isabel relative to the dual-Doppler lobes from the SMART radar deployment. The dashed circular rings indicate the operational radar range. The stippled region is the area available for dual-Doppler analysis. SR-1 (R1) is located to the north, and SR-2 (R2) is located to the south. The yellow line is the path of Hurricane Isabel. Note that the hurricane tracked directly through the eastern lobe of the dual-Doppler coverage area.

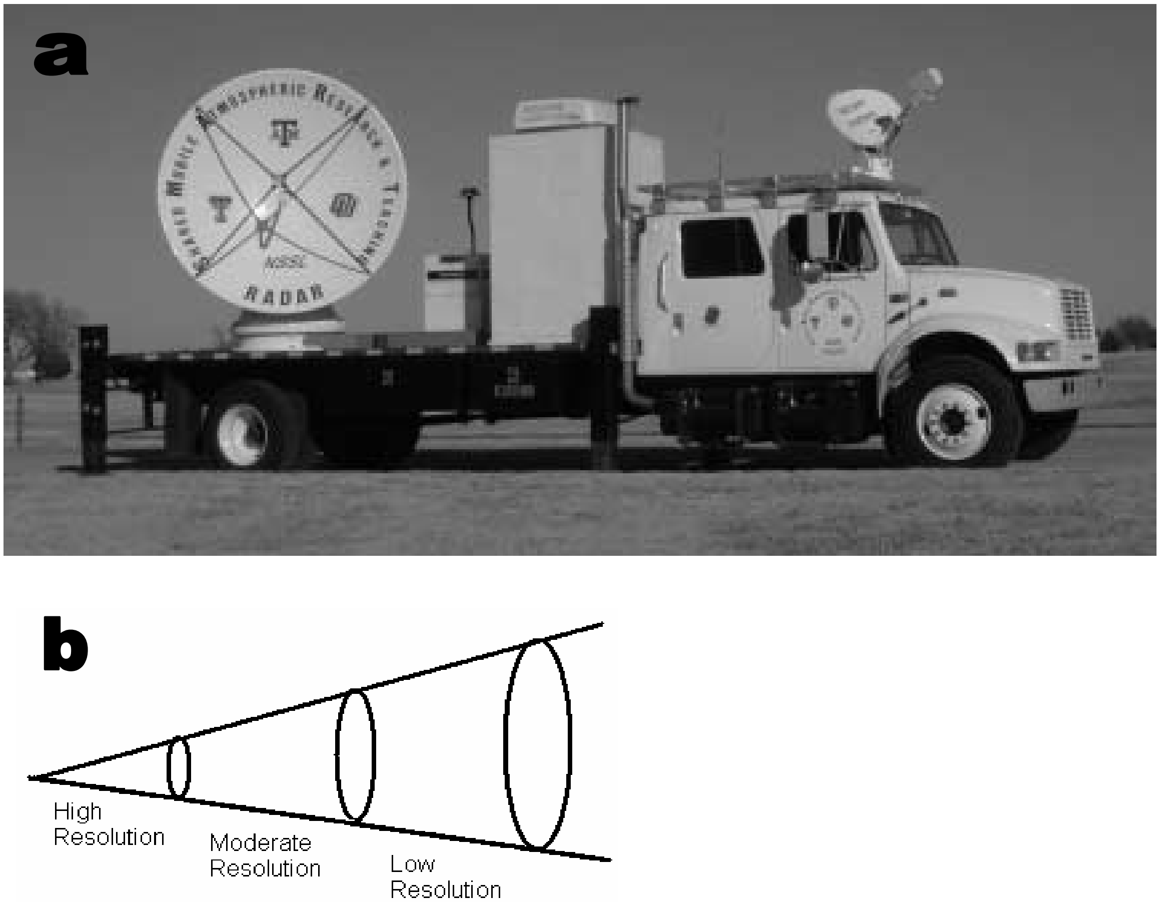
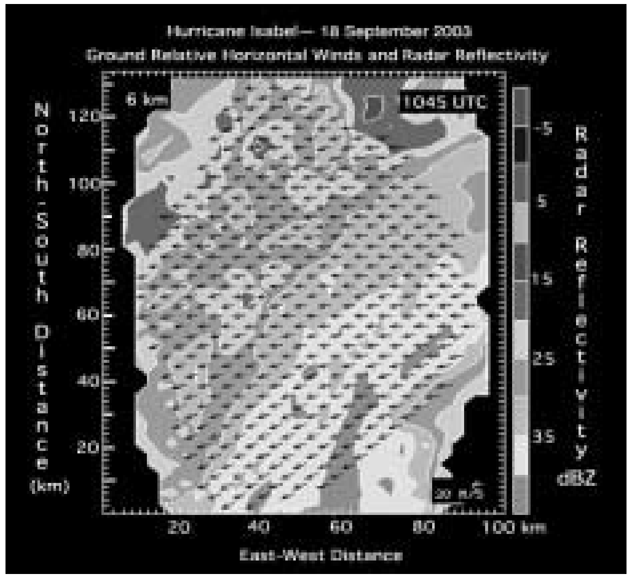


Figure 4. (a) Side view of SMART-R. (b) Illustration of limitation of radar beam width. As the beam travels outward, it loses resolution, meaning the most accurate data are closest to the radar.



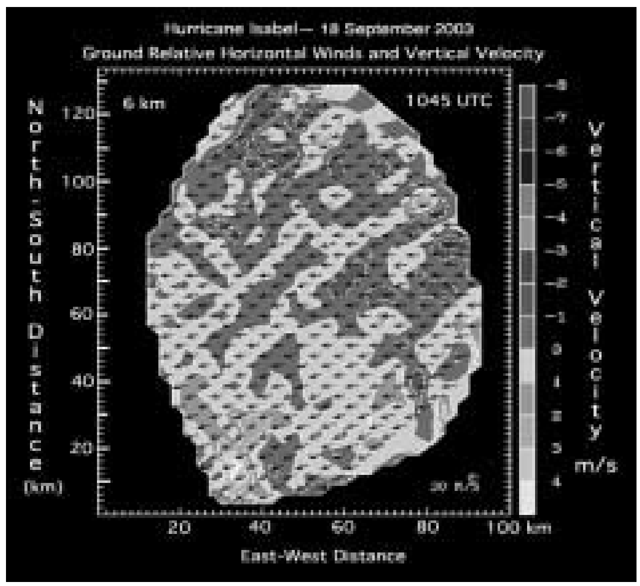


Figure 5. Top panel shows radar reflectivity at a height of 6 km at 1045 UTC with horizontal winds superimposed on it. The magnitude of reflectivity (dBZ) is given by the color scale. Bottom panel shows vertical velocities with the horizontal winds superimposed on it. The magnitude of the vertical velocity (m s^{-1}) is given by the color scale.

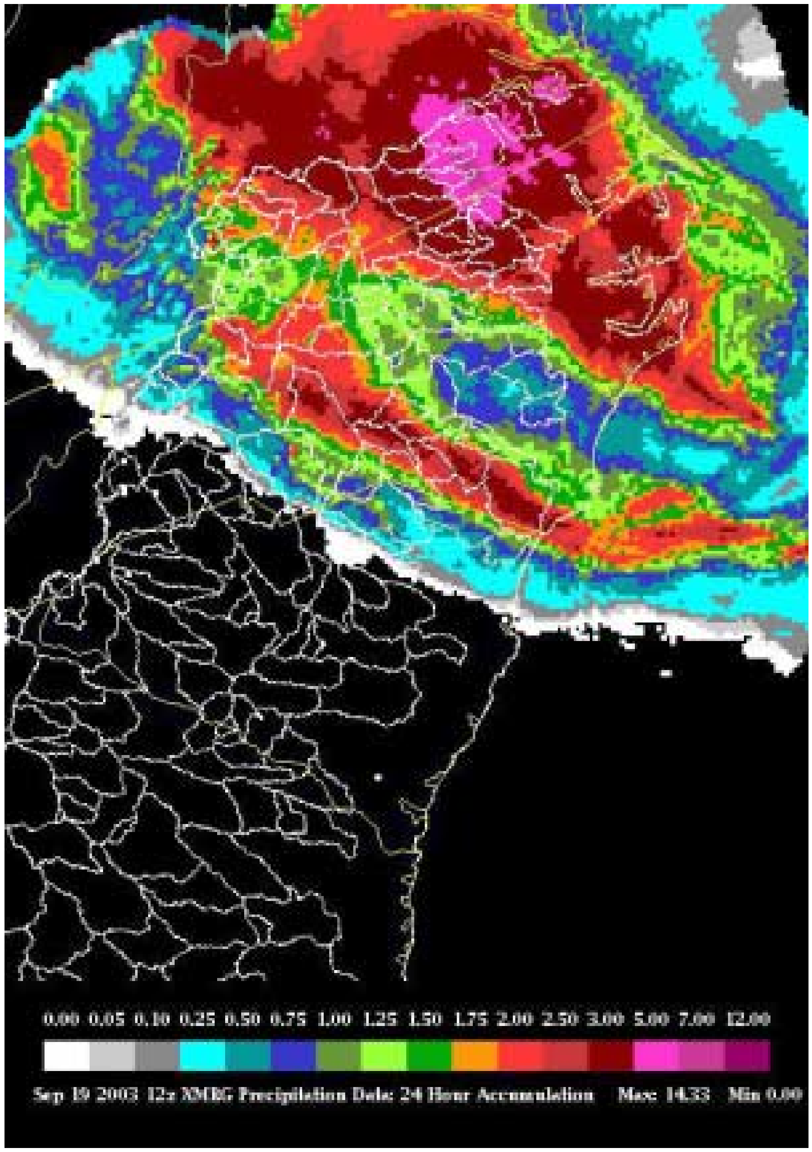


Figure 6. Radar estimated rainfall from the WSR-88D located in Moorehead City, N. C.

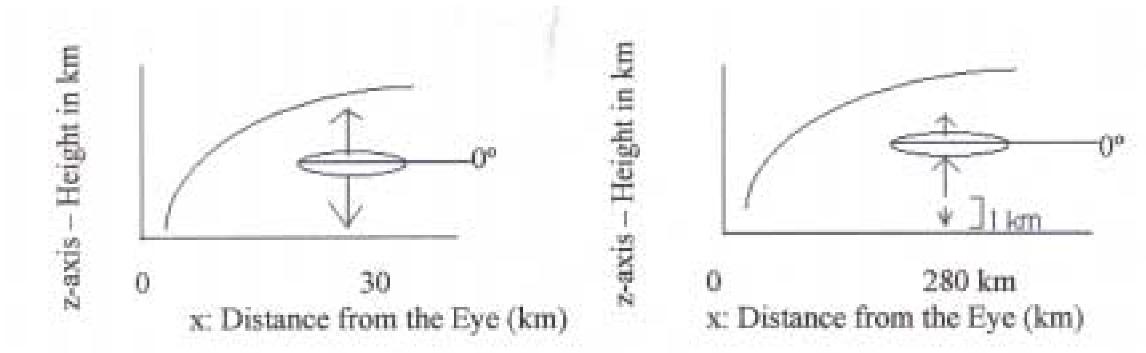


Figure 7. Left panel summarizes the conceptual model of Marks and Houze (1987). The mesoscale updraft and downdrafts are equal in magnitude and originate from the melting level. Right panel summarizes the results of this study. Note that there is a weaker updraft above the mesoscale stratiform region, a relatively strong updraft below the region, and then a weak downdraft at and below 1 km.

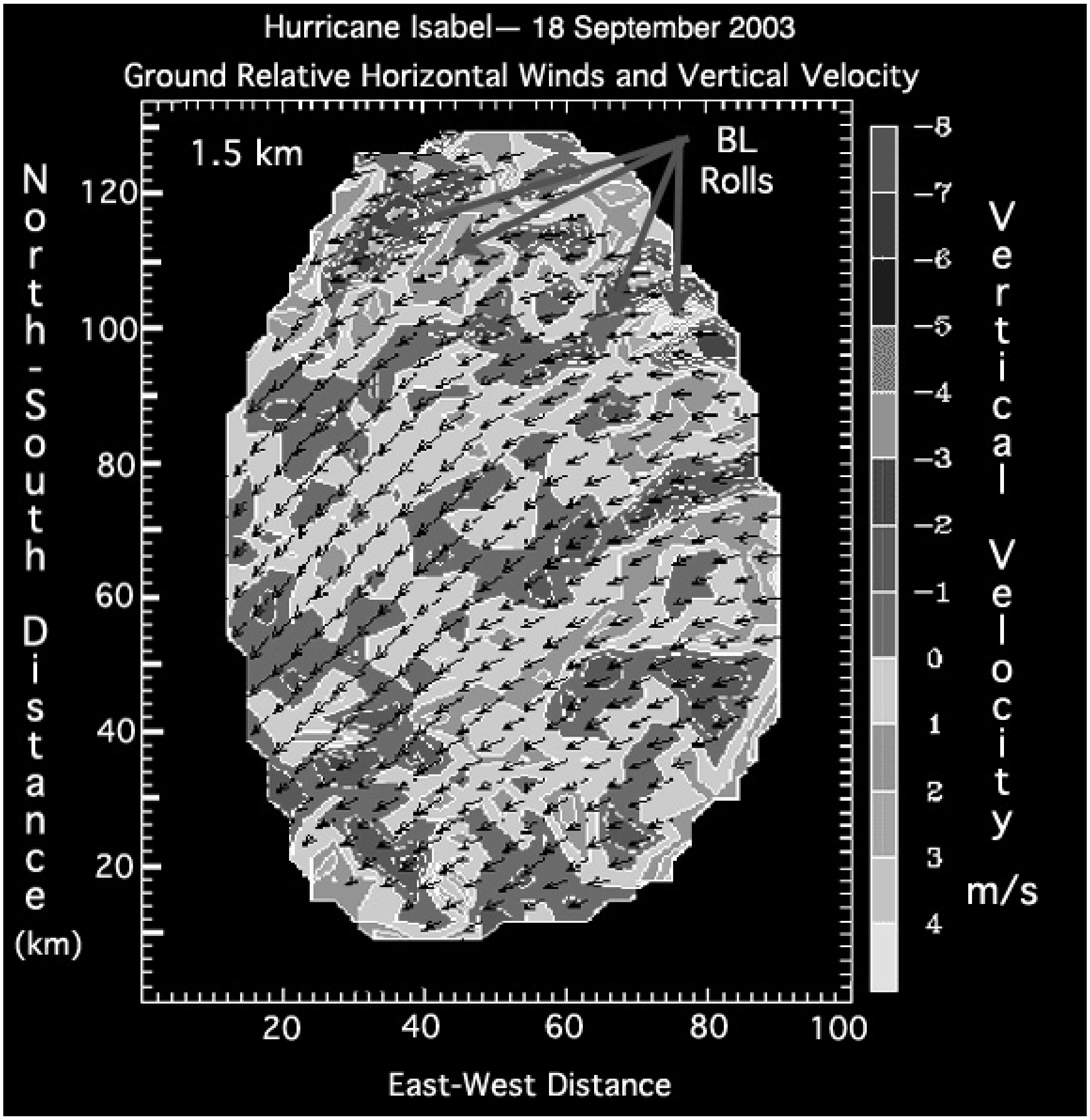


Figure 8. Vertical velocity, according to the color scale, and ground-relative horizontal winds at 1.5 km from the 1045 UTC analysis. Note the location of vertical velocity couplets associated with boundary layer rolls as indicated by the arrow.

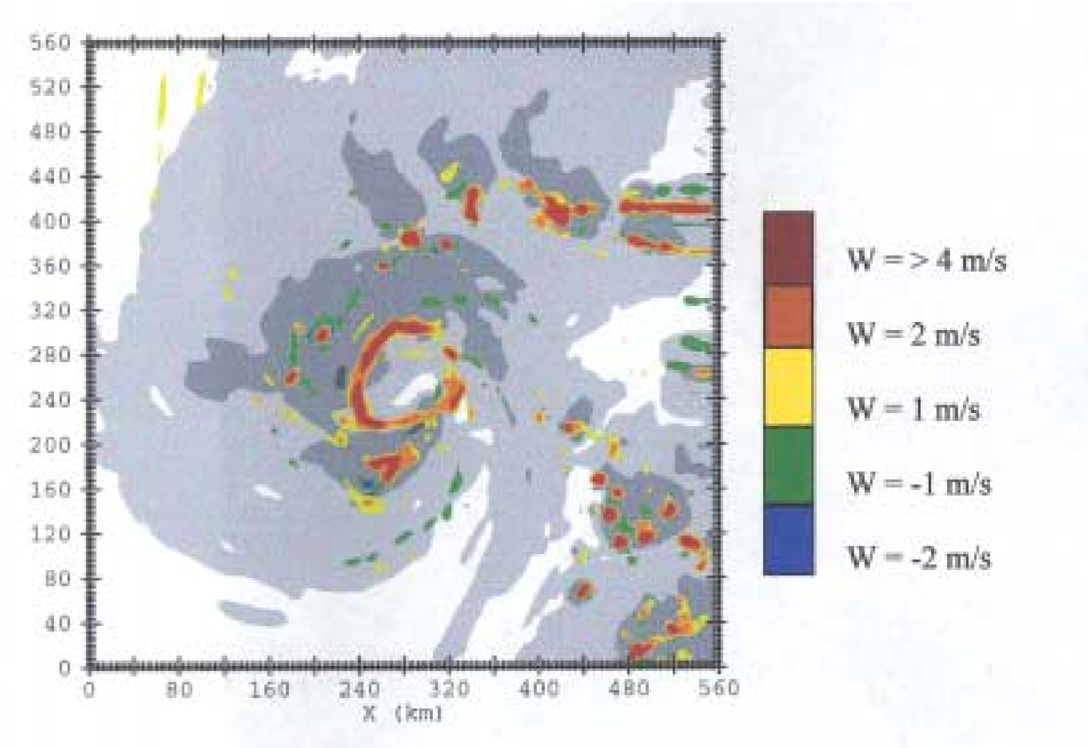


Figure 10. Numerical simulation of Hurricane Charlie. Gray shading indicates cloud regions with 6 km altitude vertical drafts overlaid in color with magnitudes given by the color scale.