

**Background Paper:
Hurricane Katrina and Double Eyewalls**

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INTRODUCTION

This paper provides background information on the Coastal Weather Research Center's work in identifying and understanding the phenomenon of "double eyewall" hurricanes, and specifically how this innovative research provides new insights into why Hurricane Katrina was as powerful and destructive as it was.

COASTAL WEATHER RESEARCH CENTER

The Coastal Weather Research Center at the University of South Alabama is the home to national experts on hurricanes. For the past decade, our work has covered:

- Forecasting hurricanes
- Measuring size/intensity of storms
- Understanding the structure and dynamics of hurricanes and their impact/ capacity for destruction
- Identifying extreme surface winds within areas of heavy hurricane rainfall

For more information, see our website: <http://www.southalabama.edu/cwrc/>

KEY ISSUE

Following Katrina, questions were raised about why the storm was so destructive.

- *Katrina had an extremely low pressure in the eye (920 millibars) at landfall – the third lowest ever recorded – why then did it only register as a Category 3 storm?*
- *If the winds were "only" Category 3, why was there such extensive wind and storm surge damage?*

Predominant images of the damage from Katrina focus on the flooding in New Orleans caused by the breaking of the levees, which resulted in the highest proportion of the loss of life and property. However, had the levees not broken, Katrina would still have been one of the most destructive hurricanes of all time because of the extreme wind and water forces created by the storm.

DOUBLE EYEWALL HURRICANES

The Coastal Weather Research Center has determined that an explanation for the extensive destruction is that Hurricane Katrina was a “double eyewall” storm when it crossed the Gulf Coast.

Double eyewall hurricanes have two concentric rings in which the highest winds are focused. They undergo a cyclical change over portions of the hurricane’s life, known as the eyewall replacement cycle. As the outer eyewall develops from a merger of spiral rainbands, it gains strength and saps energy from the inner one. Eventually, the inner eyewall disappears altogether. The outer eyewall then grows smaller and tighter around the eye, and it gains in intensity (Willoughby et al., 1982 and Willoughby 1990).

Double eyewalls develop most often in the more powerful hurricanes (Willoughby 1990). Approximately 70% of the Atlantic and 50% of the East Pacific intense storms reached concentric or double eyewall status over the period 1997-2005 (Hawkins et al., 2006).

For example, Hurricane Ivan in 2004 underwent several eyewall replacement cycles as its intensity fluctuated between Category 3 and Category 5 over its 14 day trek from near Africa to the Alabama Coast. In one instance, Ivan displayed double eyewalls while passing south of the Cayman Islands in the Caribbean; the inner eyewall completely missed the islands, with the storm center passing about 35 miles to the south. However, the outer eyewall made a direct hit, producing sustained winds measured at 150 mph, gusting to 171 mph; 95 % of the buildings were destroyed (Stewart, 2004). The following year, when Katrina was over the Gulf of Mexico, it became a Category 5 storm, with an aircraft-released dropsonde instrument measuring wind speeds of about 270 mph at 600 meters above the sea (Henning, 2006). Shortly thereafter, Katrina developed double eyewalls. As it made landfall on the Gulf Coast, the storm was in the process of an eyewall replacement cycle, meaning that the outer wall was just beginning to sap energy from the inner eyewall, enabling both eyewalls to have strong winds (Blackwell et al., 2007).

Generally, double eyewall storms have a broader “wind field” than single eyewall storms, and they produce a “one-two” punch as each eyewall makes landfall. The winds push water toward the shore, and this water surge is greatest when the eye crosses the coast.

The existence of double eyewall storms is increasingly the subject of meteorological research. Conventional visible and infrared images from satellites cannot detect the inner structure of the storm, as they cannot “see through” the cloud cover. Therefore, conventional imagery was unable to reveal the existence of two distinct eyewalls. However, microwave satellite imagery now available from NASA and Department of Defense satellites has given scientists a clearer look into what is going on inside the storm. The Cooperative Institute for Meteorological Satellite Studies (CIMSS) at the University of Wisconsin runs the Morphed Integrated Microwave Imagery at CIMSS program (MIMIC). This program specifically deals with developing algorithms that collect and synthesize microwave imagery to measure storm intensity, location and structure, including double eyewalls. This process gives forecasters better tools with which to assess the danger and impact of an approaching hurricane. For more information, see: <http://cimss.ssec.wisc.edu/tropic/real-time/marti/marti.html>

Meteorologists continue to use data from sensors dropped from airplanes traveling through the hurricane, known as “dropsondes.” Data from these dropsondes are used to complement information gained through microwave imagery and other sources. This technique has helped to determine that winds between 400 and 600 meters above the ground often far exceed the strength of sustained winds near the ground, which are used to label the category of the storm on the Saffir-Simpson scale. Data from dropsondes reveal that winds in a hurricane eyewall are often about 25% stronger at 400-600 meters altitude, as compared to the surface (Franklin et al., 2003). These intense winds are much closer to the ground than we thought 15 years ago.

Here are some other aspects of winds in a hurricane:

- Typically, hurricane gusts are about 1.3 times the sustained wind speed (Kramer and Marshall, 1991; Powell et al., 1991).
- Convective wind gusts may approach values twice that of the sustained wind (Powell et al., 1991; 2003).

- Heavy rains in convection can bring the highest winds, which usually occur in the eyewall at 400-600 meters above sea, down to the ground, resulting in very strong gusts (Holmes et al, 2006, Henning 2006).

HURRICANE KATRINA

The following conclusions specifically in relation to Katrina were presented to the 27th Conference on Hurricanes and Tropical Meteorology in April 2006 (Henning 2006 and Holmes et al., 2006) and to the 61st Interdepartmental Hurricane Conference in March 2007 (Blackwell et al., 2007), but have not otherwise been reported.

Blackwell et al., 2007 found that:

- Microwave satellite imagery shows that Katrina was a double eyewall storm when it hit New Orleans and the Mississippi Coast.
- The existence of a double eyewall pattern was also depicted by aircraft-borne Doppler radar and recorded in aircraft logs by meteorologists on board NOAA aircraft flying through Katrina at landfall.
- Katrina had recently formed a double eyewall before hitting the coast and was in the process of an eyewall replacement cycle. The inner wall was weakening, but the outer one was strengthening.
- The entire Mississippi Coast suffered the impact of at least one eyewall in Katrina; much of the coast experienced two eyewall impacts.
- The outer eyewall began hitting the Mississippi Coast up to four hours before the peak of the storm surge accompanying the inner wall. With the winds swirling counter-clockwise around Katrina, initial winds accompanying the outer eyewall would have been blowing from east to west, which would have paralleled the Mississippi coast and thus would have preceded the highest storm surge by several hours. The highest storm surge would have occurred when the winds shifted to a south-to-north (i.e., onshore) direction.
- For some locations, it took the entire day for strong winds to pass through.
 - On Dauphin Island AL, one of the few surviving weather stations in Katrina's path recorded tropical storm or hurricane force winds for 20 consecutive hours... and it was outside the reach of either eyewall.
 - A buoy 70 miles south of the Alabama/Mississippi state line recorded winds of at least tropical storm force for 30 consecutive hours.
- The disastrously high storm surge of up to 28 feet would have coincided with landfall of the **inner** eyewall and storm center.

Wind Speed

Research conducted by Richard Henning (Henning 2006) of the Air Force Reserve's 53rd Weather Reconnaissance Squadron has shown:

- Gusts measuring as high as 206 mph were detected in Katrina over the central Gulf, one of the strongest hurricane winds ever recorded by an aircraft..
- On the day before landfall, an aircraft-released dropsonde measured wind speeds of about 270 mph at 600 meters above the ocean. If valid, this would be the highest hurricane wind ever recorded by a dropsonde.
- An aircraft-released dropsonde recorded a wind in Katrina's eyewall of 153 mph at 350 meters above the beach in Pass Christian MS.

Holmes et al., 2006 shows that

- Convection, the vertical movement of air caused by powerful thunderstorms, can potentially bring some of the highest wind speeds in the eyewall down to the ground in the form of powerful gusts; this was most active in the eastern part of Katrina's eyewalls along the Mississippi coast.
- Millions of tons of water suspended several kilometers above the surface can collapse to the surface in heavy convective thunderstorms, producing downbursts and extremely damaging wind gusts.

Downbursts may have accounted for extensive blow-down of forests in southern Mississippi. The director of the Jackson County Emergency Operations Center in Pascagoula witnessed the winds gusting near 135 mph while the roof was blowing off during Katrina. Heavy rain blowing horizontally in these downbursts may have added to the wind's destructive power as it impacted structures, particularly near the waterfront, a topic for wind engineers to assess.

PREPAREDNESS

The work on double eyewall hurricanes is relevant in several ways:

- In order to assess accurately the true impact of a hurricane at landfall, the correct structure of the storm must be identified. The damage swath from a single-eyewall storm is often much narrower than a storm containing two eyewalls.
- The analysis is an essential component in warning a wide geographical area on how the storm will descend on to the community.
- Detecting double eyewall structures is vital to predicting the power of the storm. In addition to the existence of a “one-two” punch created by the two eyewalls, there is likely a significant difference how the ocean responds to a large double eyewall storm, compared to a small single eyewall storm. This could have drastic implications on the behavior of the storm surge, such as the timing of the arrival of strong winds vs. high water, and the ultimate height, expanse, and persistence of the storm surge.
- The meteorological findings call for the construction of buildings that will withstand the prolonged pounding that a double eyewall storm may inflict. In addition, buildings must be able to sustain their integrity during multiple one to three second powerful bursts that often reach speeds 30% higher than the sustained winds. Building codes in coastal areas need to be rigorous and enforced.
- The findings are providing improved post-storm analysis of cause of damage – eg, potential of wind before water as a significant cause of destruction.
- The eyewall replacement cycle that describes the structural transition of a storm between one and two eyewalls is one of the most important elements in correctly forecasting the intensity of a landfalling storm. Currently, this forecasting capability is either absent or (at best) only crudely accounted for in multi-day hurricane forecasts, and it is a significant reason for only very slow improvement in intensity forecast accuracy over the last couple of decades.

FORECAST

Several factors point to the increased chance of high hurricane activity in 2007:

- A weaker-than-normal jet stream influence in the tropical Atlantic and reduced wind shear; stronger shear decreases hurricane frequency and intensity.
- Abnormally warm temperatures in the North Atlantic Ocean.
- Likely development of a La Nina (last year, the development of an El Nino sapped energy from the Atlantic hurricane environment, which is unlikely this year).

There is a natural cycle of approximately 50-60 years for Atlantic hurricane activity (Klotzbach and Gray, 2006). We have been in an **active** period since the mid-90s. From available data, enhanced periods appear to last approximately 25-30 years; we are likely to have at least 15-20 more years of the current cycle.

While **inactive** periods also persist for 25 to 30 years; the most recent began in the 1960s, coinciding with tremendous growth in development in the hurricane-prone Gulf and Atlantic coasts. This rapid coastal development during a time of fewer hurricanes has now set the stage for unprecedented damage from landfalling storms in this more active phase of the multi-decadal hurricane cycle.

CURRENT PROJECTS

Current hurricane research projects include:

- A number of universities on the Gulf Coast are installing “mesonets” consisting of a dense array of low-cost weather stations that can provide measurements of crucial when storms make landfall. Dr. Sytske Kimball (skimball@usouthal.edu) of the Coastal Weather Research Center and Department of Earth Sciences at the University of South Alabama (USA) is working on the installation of a mesonet across coastal regions of Alabama and Mississippi, as well as the offshore waters. Also under the direction of Dr. Kimball, the University is partnering with NOAA’s Environmental Modeling Center and the Atlantic Oceanographic and Meteorological Laboratory to install a Center for Hurricane Intensity and Landfalls Investigations (CHILI) on the USA campus.
- Naval Research Laboratories, Office of Naval Research, and NOAA have sponsored the CIMSS – the Cooperative Institute for Meteorological Satellite Studies – at the University of Wisconsin. This institute provides real-time images of developing hurricanes and conducts research in environmental studies. <http://cimss.ssec.wisc.edu/>
- CIMSS and NRL produce microwave satellite imagery of hurricanes. The former runs the Morphed Integrated Microwave Imagery at CIMSS program (MIMIC). This program specifically deals with developing algorithms that collect and synthesize microwave imagery used define a hurricane’s structure and provide reliable estimates of hurricane intensity. <http://cimss.ssec.wisc.edu/tropic/real-time/marti/marti.html>
- NOAA maintains the Joint Hurricane Testbed (JHT) program, which feeds research into operations at the National Hurricane Center. The JHT receives funding from NOAA, NASA, the Navy, private companies, and state and private universities. <http://www.nhc.noaa.gov/jht/>
- The Hurricane Research Division (HRD) at NOAA’s Atlantic Oceanographic and Meteorological Laboratory is engaged in advancing the basic physical understanding and improving the forecasts of [hurricanes](#) and tropical meteorological systems. A key aspect of HRD's activity is its [annual field program](#) of flights aboard [NOAA's research aircraft \(two WP-3D turboprops and a Gulfstream IV-SP jet\)](#) flown by NOAA's [Aircraft Operations Center](#). HRD maintains a web page that provides information on various hurricane research programs and data sets. <http://www.aoml.noaa.gov/hrd/>
- US Senator Mel Martinez of Florida has introduced S. 931 – “A bill to establish the National Hurricane Research Initiative to improve hurricane preparedness, and for other purposes.” If made into law, the bill would begin to improve resources for better understanding of hurricane structure, including multiple eyewall issues and how they affect intensity analysis and forecasting. <http://www.govtrack.us/congress/bill.xpd?bill=s110-931>
- The Joint Typhoon Warning Center is supported by the Navy and Air Force and is responsible for issuing warnings in the Pacific and Indian Oceans. <https://metocph.nmci.navy.mil/jtwc.php>
- Since 1998, the 53rd Weather Reconnaissance Squadron (53rd WRS), also known as *The Hurricane Hunters*, of the Air Force Reserve, has regularly provided NOAA with data gathered from “dropsondes” – sensors dropped from aircraft into the storm – that use GPS technology, enabling detection of wind speed closer to the ground than previously possible. <http://www.403wg.afrc.af.mil/library/factsheets/factsheet.asp?id=7483>

REFERENCES

Blackwell, K. G., P. Fitzpatrick, C. Velden, and T. Wimmers, 2007: Double (concentric) eyewalls in Hurricane Katrina at landfall: A key to the storm’s huge size and devastating impact over a three-state coastal region, *61st*

Interdepartmental Hurricane Conference, Office of the Federal Coordinator for Meteorology, New Orleans, LA, March 2007.

http://www.ofcm.gov/ihc07/linking_file_ihc07.htm

Fortner, L. E., 1958: Typhoon Sarah, 1956. *Bulletin of the American Meteorological Society*, Volume 39, pp 633-639.

Franklin, J. L., M. L. Black, and K. Valde, 2003: GPS dropwindsonde wind profiles in hurricanes and their operational implications. *Journal of Weather and Forecasting*, Volume 18, pp 32-44.

<http://ams.allenpress.com/perlserv/?request=get-pdf&doi=10.1175%2F1520-0434%282003%29018%3C0032%3AGDWPIH%3E2.0.CO%3B2>

Henning, R. G., 2006: The intensity of wind gusts underneath areas of deep eyewall convection in Hurricanes Katrina and Dennis at landfall," 27th Conference on Hurricanes and Tropical Meteorology, American Meteorological Society, Monterey, CA, April 2006, Paper 3B.1.

http://ams.confex.com/ams/27Hurricanes/techprogram/paper_108816.htm

Hawkins, J., M. Helveston, T. F. Lee, F.J. Turk, K. Richardson, C. Sampson, J. Kent, and R. Wade, 2006: Tropical cyclone multiple eyewall configurations, 27th Conference on Hurricanes and Tropical Meteorology, American Meteorological Society, Monterey, CA, April 2006, Paper 6B.1.

http://ams.confex.com/ams/27Hurricanes/techprogram/paper_108864.htm

Holmes, J., K. G. Blackwell, R. A. Wade, and S. K. Kimball, 2006: Collapsing precipitation cores in open-eyewall hurricanes at landfall: Are these cores actually downbursts associated with extreme surface wind gusts? 27th Conference on Hurricanes and Tropical Meteorology, American Meteorological Society, Monterey, CA, April 2006, Paper 7B.7.

http://ams.confex.com/ams/27Hurricanes/techprogram/paper_108947.htm

Klotzbach, P. J. and W. M. Gray, 2006: Causes of the unusually destructive 2004 Atlantic basin hurricane season. *Bulletin of the American Meteorological Society*, Volume 87, pp 1325-1333.

Krayer, W. R. and R. D. Marshall, 1991: Gust factors applied to hurricane winds. Preprints: *Eighth International Conference on Wind Engineering*, London, Ontario, Canada, International Association for Wind Engineering.

Powell, M. D., P. P. Dodge, and M. L. Black, 1991: The landfall of Hurricane Hugo in the Carolinas: Surface wind distribution. *Journal of Weather and Forecasting*, Volume 6, pp 379-399.

<http://ams.allenpress.com/archive/1520-0434/6/3/pdf/i1520-0434-6-3-379.pdf>

Powell, M.D., P. J. Vickery and T. A. Reinhold, 2003: Reduced drag coefficient for high wind speeds in tropical cyclones. *Nature*, Volume 422, 20 March 2003, pp 279-283

Stewart, S. R., 2004: Tropical Cyclone Report – Hurricane Ivan, NOAA National Hurricane Center, Updated 27 May 2005.

http://www.nhc.noaa.gov/pdf/TCR-AL092004_Ivan.pdf

Willoughby, H. E., J. A. Clos, and M. G. Shreihah, 1982: Concentric eye walls, secondary wind maxima, and the evolution of the hurricane vortex. *Journal of Atmospheric Science*, Volume 39, pp 395-411.

<http://ams.allenpress.com/archive/1520-0469/39/2/pdf/i1520-0469-39-2-395.pdf>

Willoughby, H. E., 1990: Temporal changes in the primary circulation in tropical cyclones. *Journal of Atmospheric Sciences*, Volume 47, pp 242-264.

<http://ams.allenpress.com/archive/1520-0469/47/2/pdf/i1520-0469-47-2-242.pdf>

ABOUT DR. BLACKWELL

Hurricane Forecaster and Research Scientist Coastal Weather Research Center

Associate Professor of Meteorology University of South Alabama

B.S. 1980 University of Wisconsin
M.S. 1987 Texas A&M University
Ph.D. 1990 Texas A&M University

Dr. Keith Blackwell joined the faculty of the Department of Earth Sciences at the University of South Alabama (USA) in September of 1996 after serving thirteen distinguished years as a meteorologist with the U.S. Air Force where he achieved the rank of Major in 1994. He subsequently spent another seven years in the USAF reserves where he served as Chief of Weather Forecast Applications with the 15th Operational Weather Squadron before retiring at the rank of Lieutenant Colonel in 2005.

Dr. Blackwell has published several journal papers on tropical weather systems, including two studies on eyewall replacement cycles, low-level wind maxima, and extreme rainfall in landfalling hurricanes. His current research is in intensity assessment and structural aspects of landfalling hurricanes. Dr. Blackwell developed a numerical hurricane track and wind profile model called the *Blackwell Over-surface Hurricane Wind* (BLOHW) Model. With the help of this model, he has provided real-time hurricane forecasts for up to 100 industrial, educational and governmental clients through USA's Coastal Weather Research Center during hurricane emergencies, including Danny (97), Georges (98), Lili (02), Ivan (04), and Katrina (05).

Dr. Blackwell teaches the capstone senior course on synoptic meteorology and forecasting at the University of South Alabama. He also teaches a tropical discussion course during hurricane season each year, as well as a summer course titled "*Hurricanes of the Gulf Coast*" at the Dauphin Island Sea Lab.

Prior to his appointment to USA, Dr. Blackwell was the Director of Meteorology at the United States Air Force Academy in Colorado Springs. While at the Academy, he served as Director of the Cadet Summer Research Program (1994-96) and was Secretary of the Weather Career Field Selection Board (1994-1996).

In addition to his teaching experience at the University of South Alabama and the Air Force Academy, Dr. Blackwell was a Lecturer in the Department of Geography at the University of Nebraska-Omaha (1992-93) and Embry-Riddle Aeronautical University (1991-92). Also he served as a Lecturer for the Department of Defense Mesoscale Modeling and Forecasting Seminar at Air Weather Service Headquarters (1992). He was also the Lead Scientist and Team Chief for the Regional Numerical Models Team at Air Force Global Weather Central in Omaha NE from 1990-1993.

Dr. Blackwell has also worked as a forecaster with Capitol Weather Service in Mobile, AL, (1981-1983) prior to joining the U.S. Air Force. In addition, he was an Air Pollution Meteorologist with Air Pollution Control in the Jefferson County Health Department in Birmingham, AL (1980-81).

Among his many awards, Dr. Blackwell has received two Meritorious Service Medals from the U.S. Air Force Academy and 15th Operational Weather Squadron, the Outstanding Educator Award for Teaching Excellence at the Air Force Academy, the Lance P. Sijan Leadership Award for Air Weather Service while at AFGWC, and recently the Dean's Lecture Award in the College of Arts and Sciences at USA (the college's highest faculty award). In addition, Dr. Blackwell was asked to testify before the U.S. Senate's subcommittee on Disaster Prediction and Prevention following the Hurricane Katrina disaster:

Video: http://commerce.senate.gov/public/index.cfm?FuseAction=Hearings.Hearing&Hearing_ID=1607

Written testimony: <http://commerce.senate.gov/pdf/blackwell.pdf>

Dr. Blackwell also received a Distinguished Graduate Student Award (one of only 5 annually) while a student at Texas A&M University in 1988.

More information at <http://www.southalabama.edu/cwrc/stfkeith.html>

ABOUT THE COASTAL WEATHER RESEARCH CENTER

The Coastal Weather Research Center, a self-supporting operation of the Department of Earth Sciences of the University of South Alabama, began operation on January 1, 1988. Located in the Mitchell Center on the main campus, the Weather Center consists of a meteorological laboratory, information center, and archive.

The Weather Center's information service is a unique operation for a university. Utilizing the latest in radar and satellite data, the Weather Center provides forecasts, warnings, and special weather information to businesses, industries and municipal governments in Alabama, Mississippi, and northwest Florida. The Coastal Weather Research Center also provides hurricane forecasting services for clients along the Gulf and Southeast Atlantic coasts of the United States. The Weather Center's computer network operates 24 hours a day providing an array of forecasts, warnings, special statements, and climatological data.

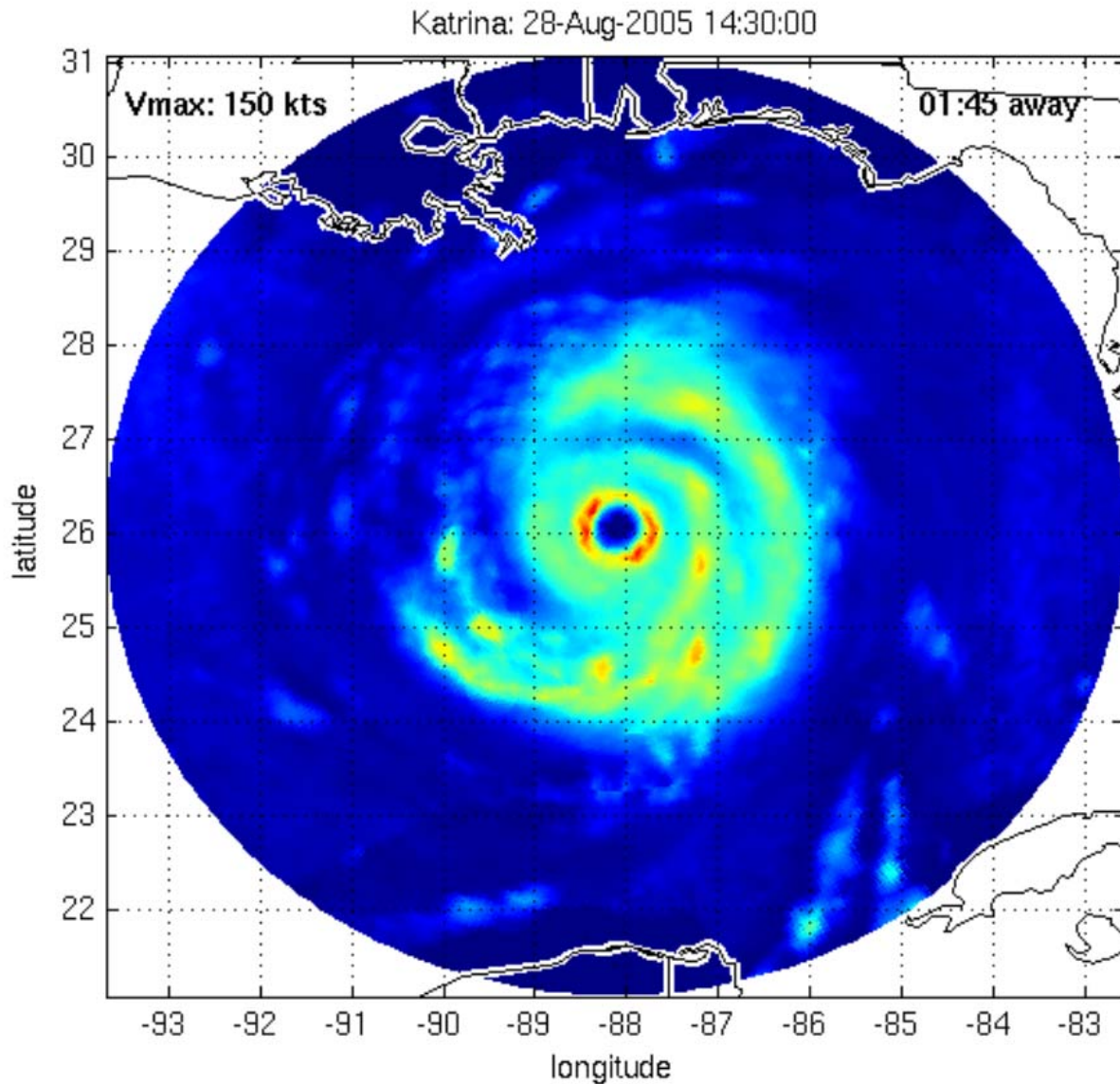
The Coastal Weather Research Center also supports the meteorology academic program at the University of South Alabama. The Center has become a focal point of the program by allowing students to utilize map products and data systems while receiving training in industrial meteorology. Through the efforts of the Weather Center and its staff, meteorology students are being prepared to work for private weather forecasting companies across the nation.

STILL IMAGES

Below is a sampling of images of double eyewall storms: Katrina, Wilma, Rita and Ivan.

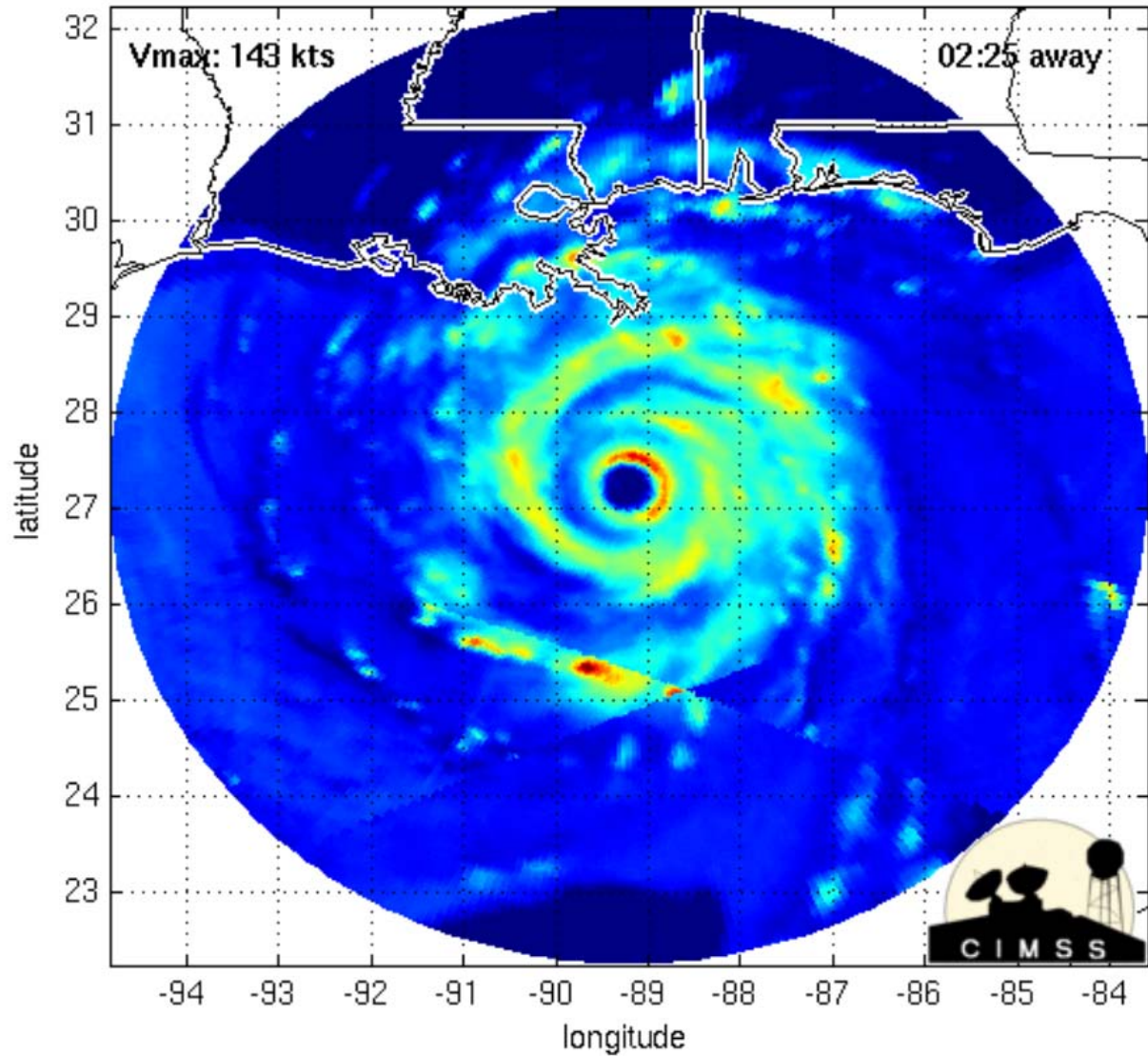
Microwave MIMIC images courtesy of UW-CIMSS Tropical Cyclone Group (Contacts: Chris Velden (PI) (chris.velden@ssec.wisc.edu) and Tony Wimmers (wimmers@ssec.wisc.edu) for MIMIC Software questions)

Hurricane Katrina, 2005:

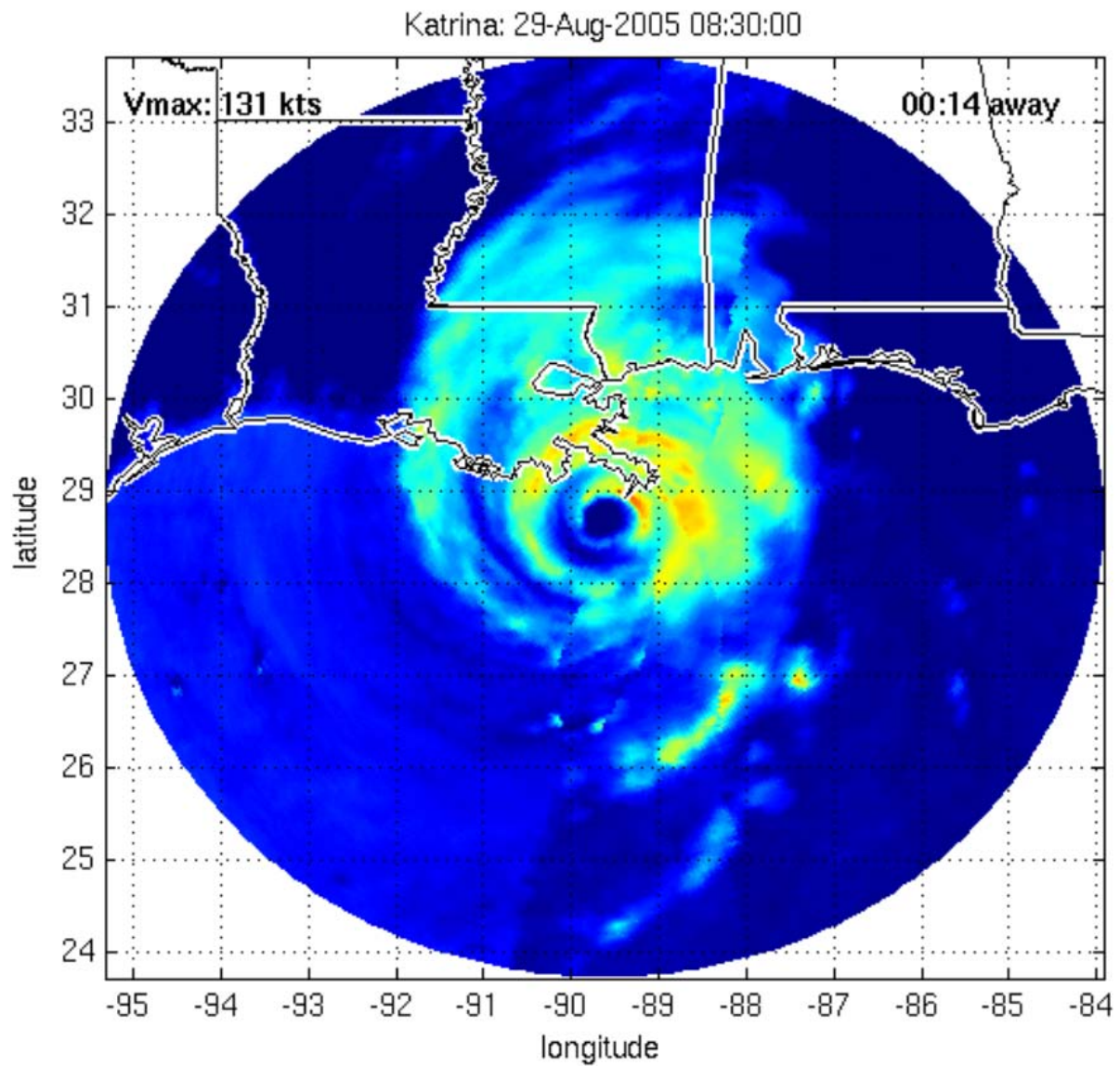


Microwave MIMIC satellite imagery of Katrina at Category 5 strength in the central Gulf at 9:30 am CDT 28 August 2005. Note the existence of a single intense eyewall in the imagery surrounding the eye.

Katrina: 29-Aug-2005 00:00:00

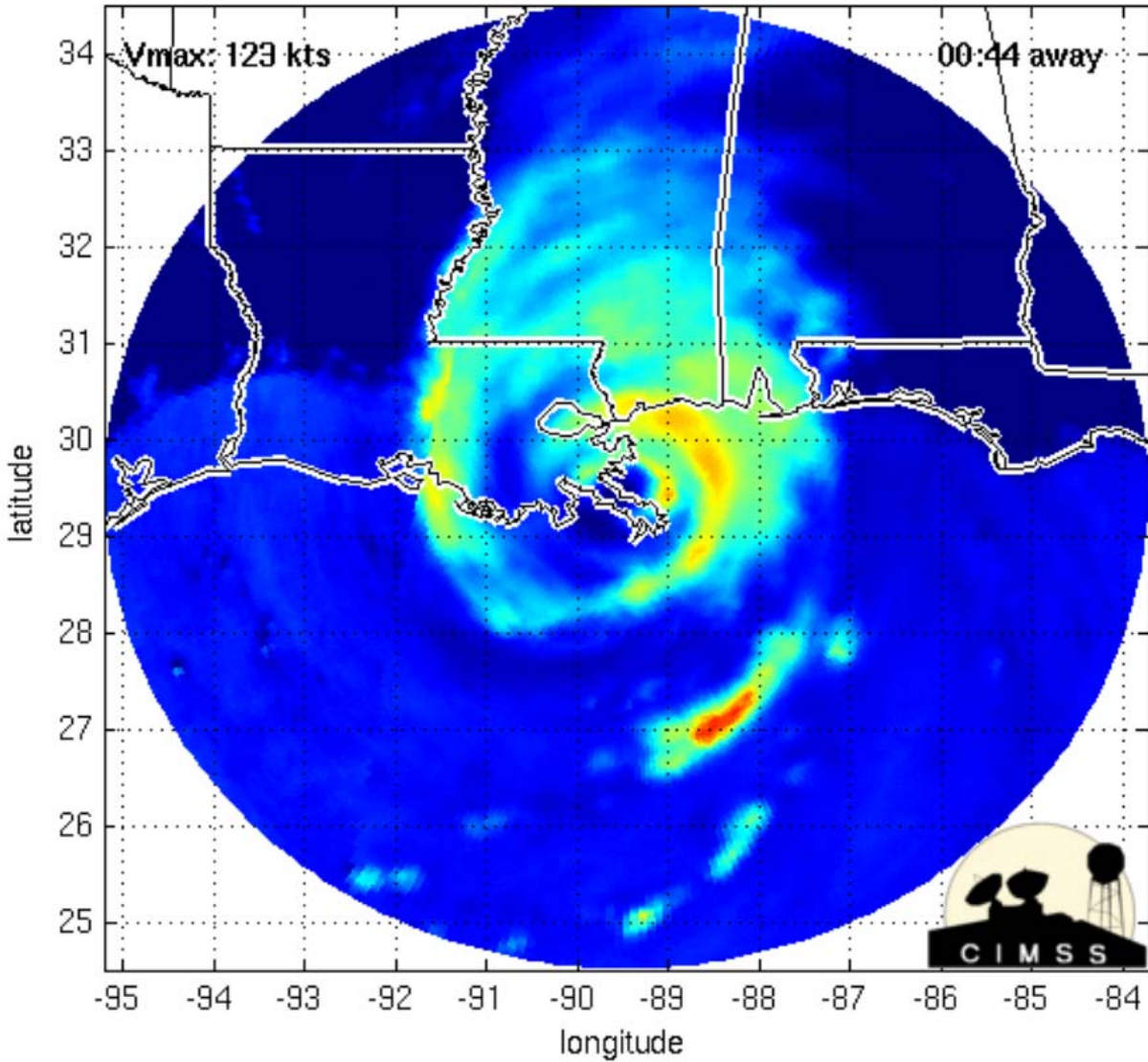


Microwave MIMIC satellite imagery of Katrina in the process consolidating its outer rainbands, eventually leading to the formation of an outer eyewall. 7:00 pm CDT, 28 August 2005. At this time, the storm still contains a single powerful eyewall.



Microwave MIMIC satellite imagery of Katrina making landfall in Louisiana with a double eyewall structure (i.e., two concentric rings around the storm center) at 3:30 am CDT, 29 August 2005. At this time, the inner eyewall is weakening as the outer eyewall is strengthening.

Katrina: 29-Aug-2005 11:45:00



Microwave MIMIC satellite imagery of Katrina showing the outer eyewall now making landfall in Mississippi with the inner eyewall and storm center still well to the south. 6:45 am CDT, 29 August 2005. At this time, the southwest portions of each eyewall are eroding due to wind shear and dry air entering the storm circulation.

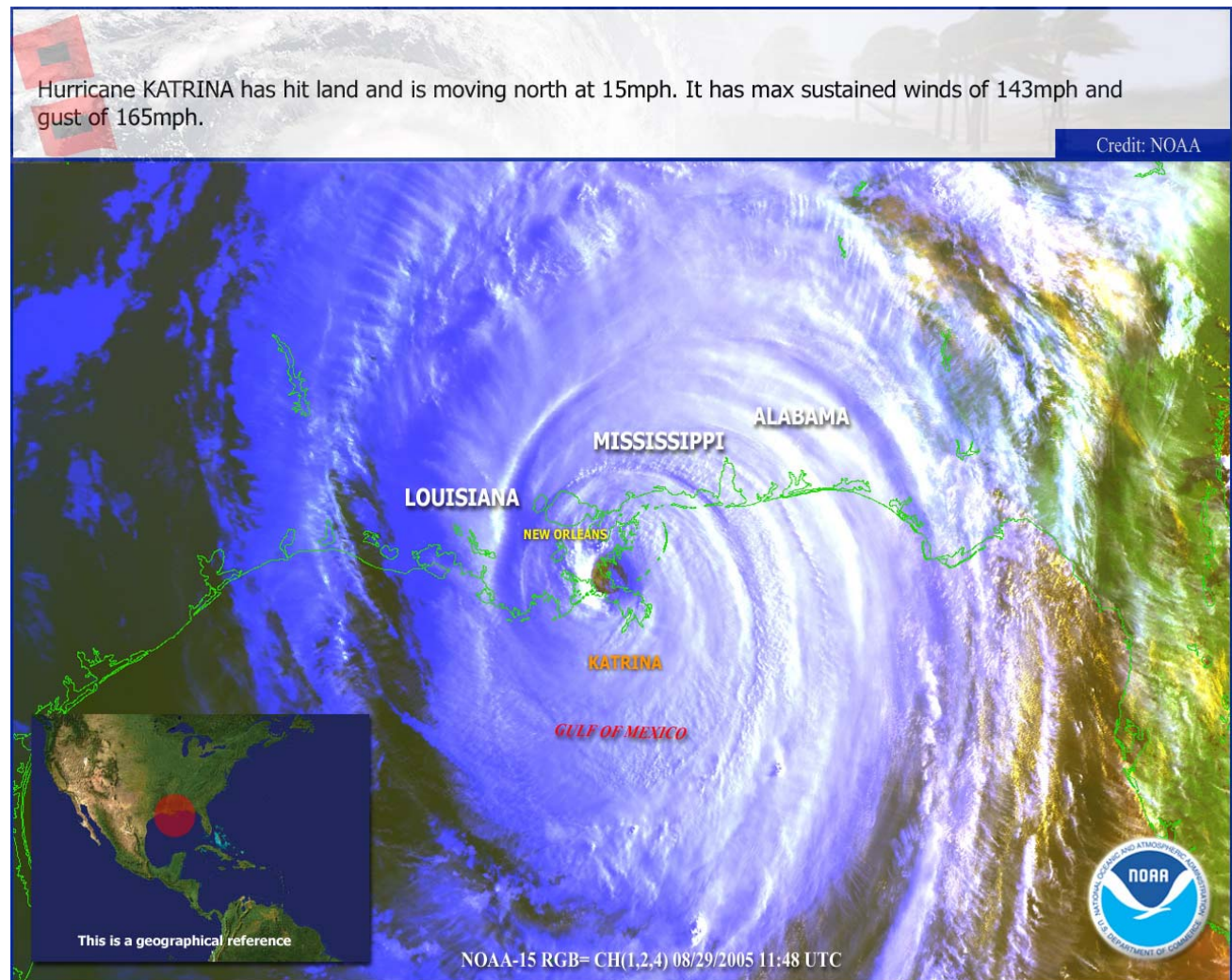
Loop video viewable at:

http://cimss.ssec.wisc.edu/tropic/real-time/marti/2005_TWELVE/webManager/displayJavaBy12hr_06.html

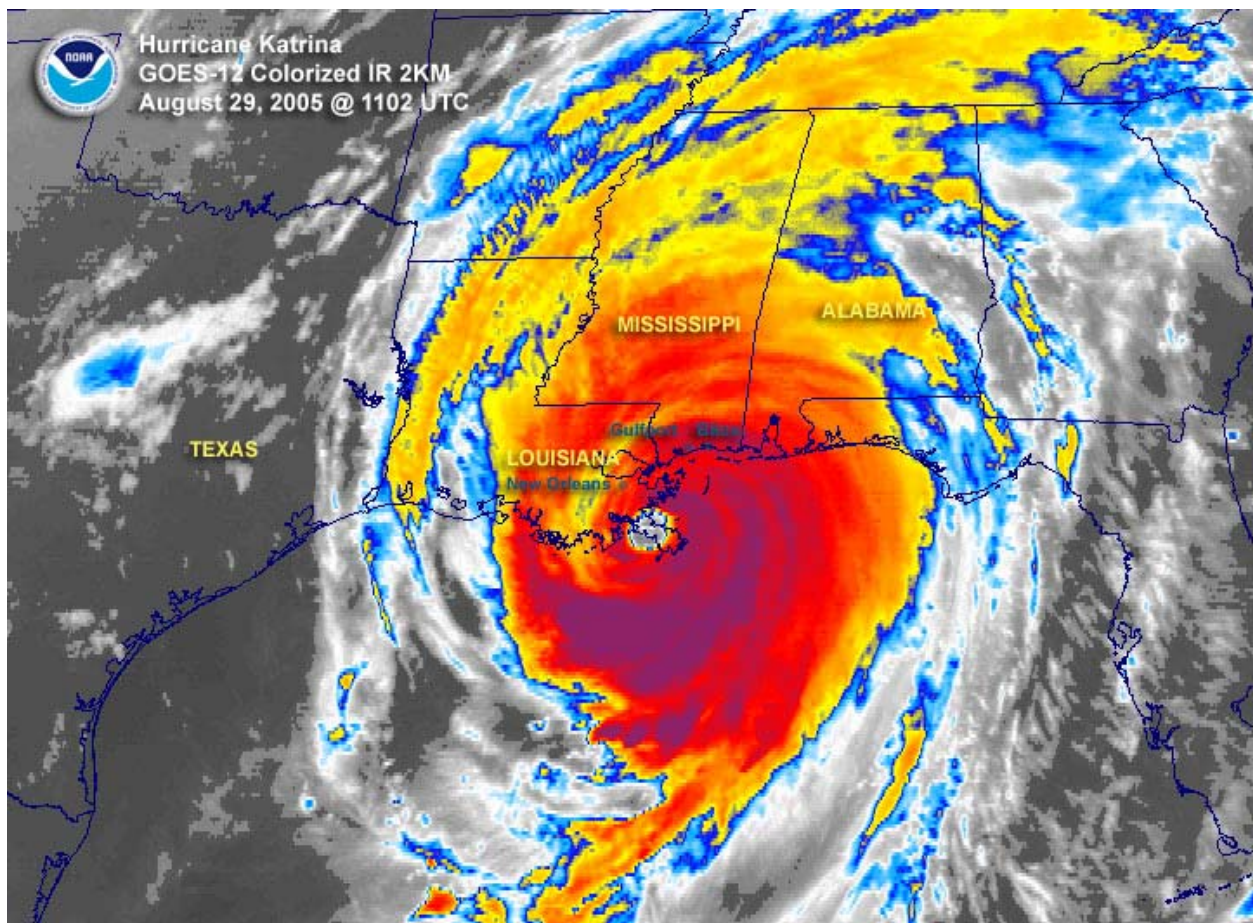
or

http://cimss.ssec.wisc.edu/tropic/real-time/marti/2005_TWELVE/webManager/displayGifsBy12hr_06.html

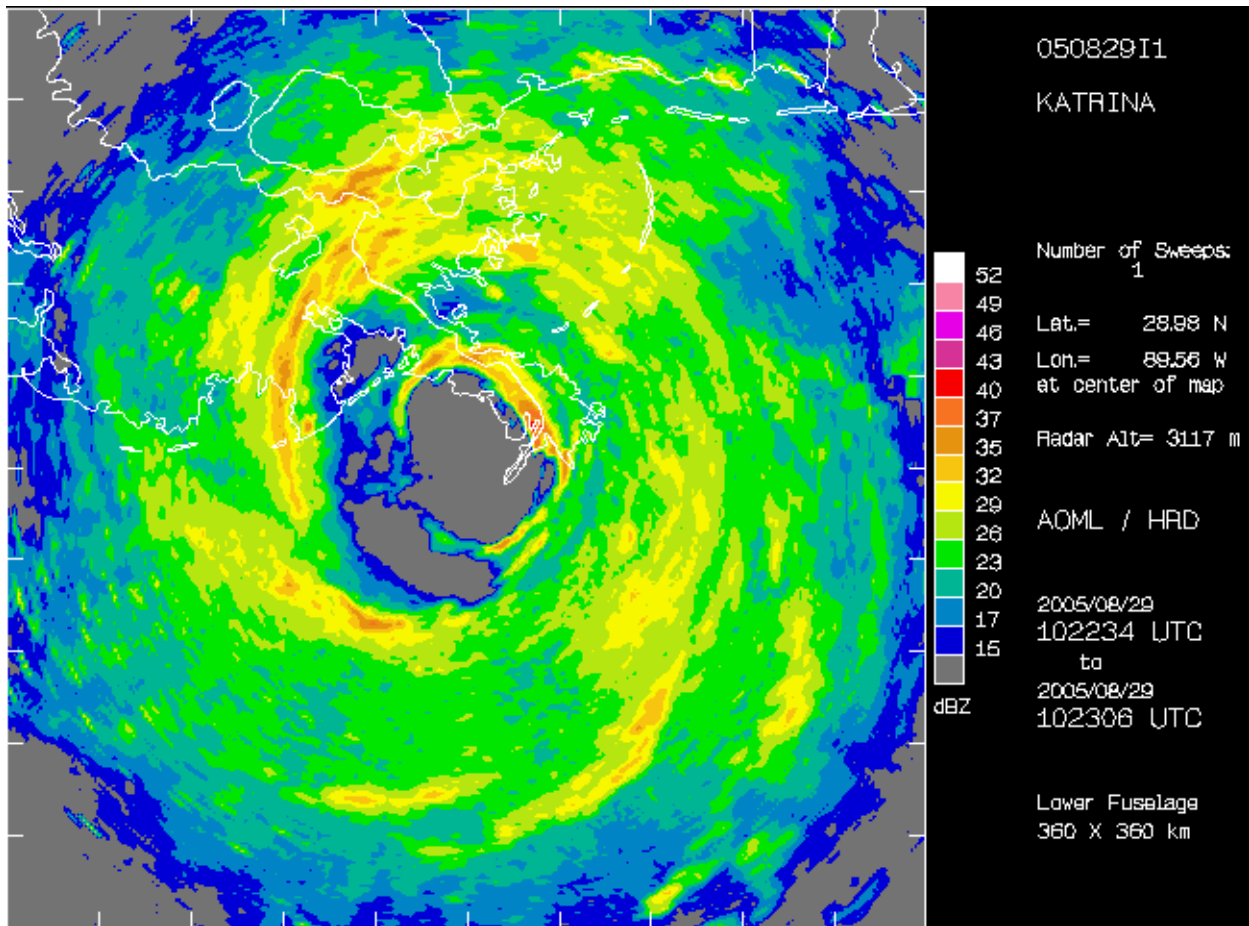
Conventional Imagery of Katrina



Visible satellite imagery of Hurricane Katrina making landfall on the northern Gulf Coast. 6:45 am CDT, 29 August 2005. Clouds at the top of the storm are masking the existence of two eyewalls within the storm. Microwave imagery, as shown in earlier images, can “see through” these clouds and reveal the eyewall structure within the storm. (Courtesy of NOAA)



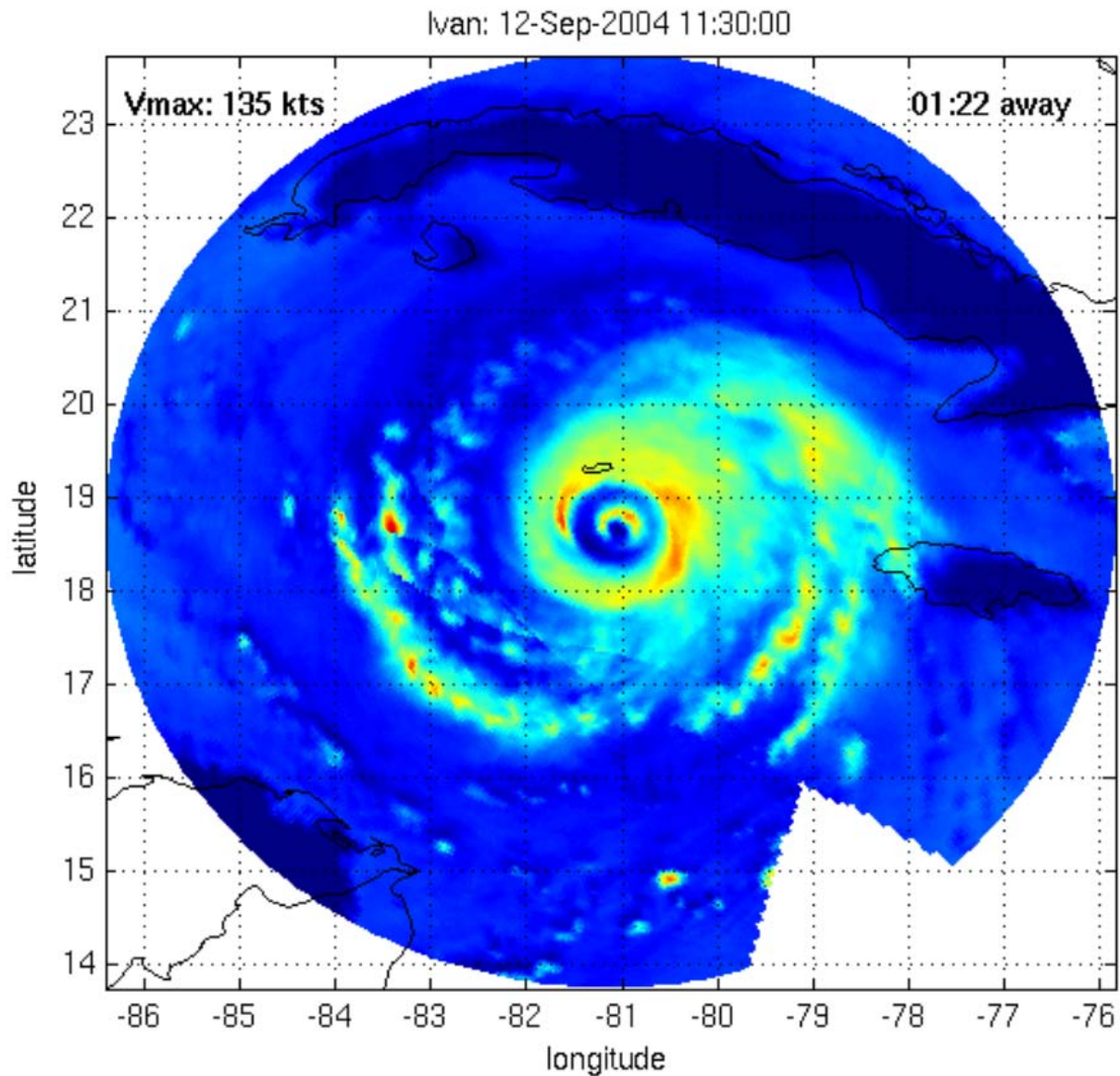
Infrared satellite imagery of Hurricane Katrina making landfall on the northern Gulf Coast. 6:02 am CDT, 29 August 2005. Again, clouds at the top of the storm are masking the existence of two eyewalls within the storm. Microwave imagery, as shown in earlier images, can “see through” these clouds and reveal the eyewall structure within the storm. (Courtesy of NOAA)



NOAA Aircraft Doppler radar imagery displaying the concentric double-eyewall structure of Katrina as the eye makes landfall in southeast Louisiana at 5:23 am CDT, 29 August 2005. (Courtesy of the Hurricane Research Division/AOML/NOAA).

Radar has long been used to identify double eyewalls in hurricanes, but the radar must be located very close to the storm in order to “see” the storm. Thus, the storm must be close to land in order for most weather radars to be useful. Some aircraft, such as the NOAA P-3 research aircraft, are equipped with on-board Doppler radar which is useful in storm penetration missions (as shown in this image). With large storms such as Katrina, radar often cannot see the entire storm due to range limitations, unless the radar is placed directly in the middle of the storm (as in this image when the aircraft was located in Katrina’s eye.)

Hurricane Ivan, 2004



Microwave MIMIC satellite imagery of Hurricane Ivan slamming Grand Cayman Island with its outer eyewall (6:30 am CDT, 12 September 2004). Although Ivan's eye and inner eyewall passed to the south of Grand Cayman, the outer eyewall made a direct hit. Winds were measured on Grand Cayman at 150 mph with gusts to 171 mph in the outer eyewall. Damage totaled \$1.85 billion with 95% of the island's buildings destroyed.

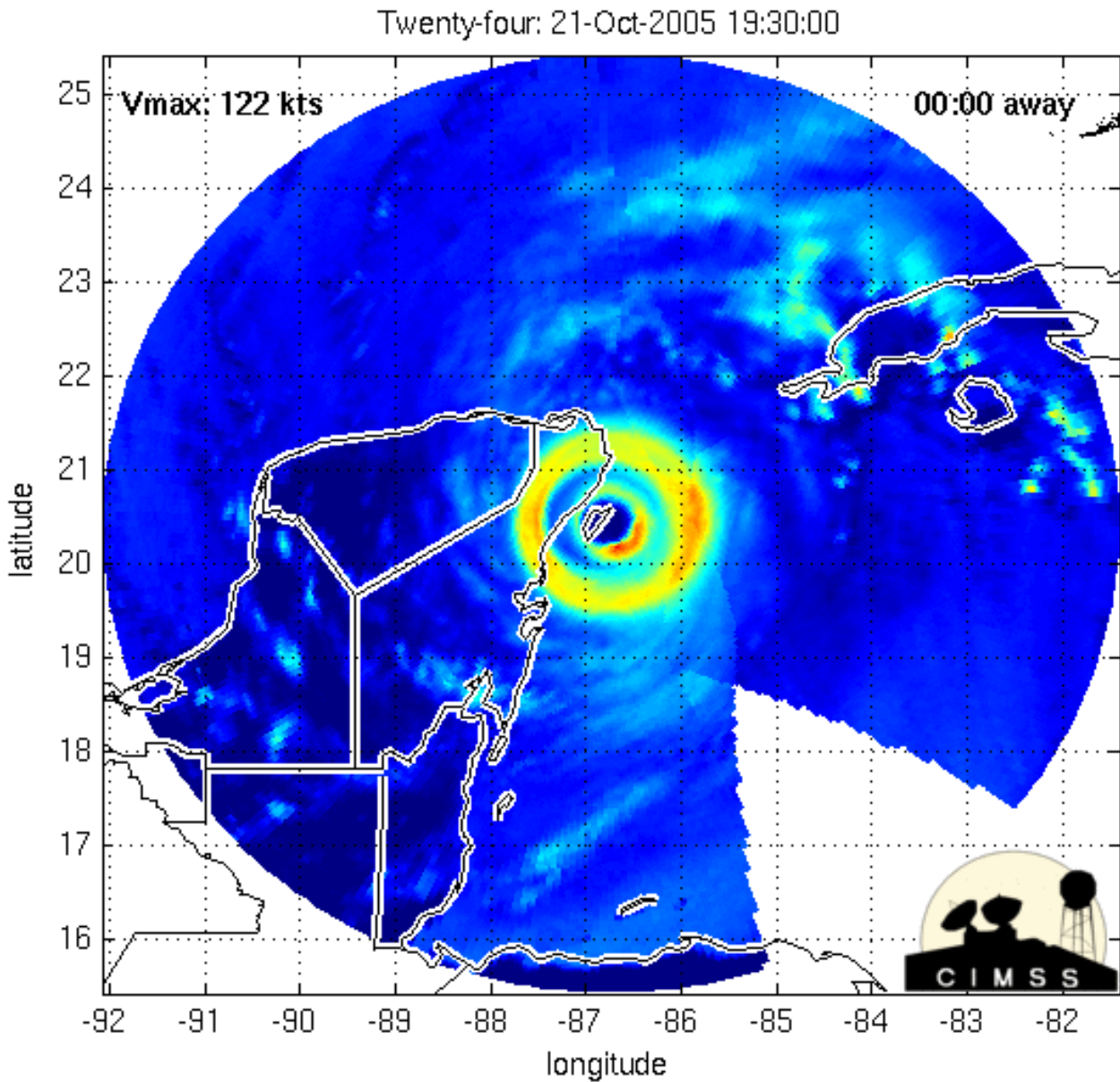
Loop video viewable at:

http://cimss.ssec.wisc.edu/tropic/real-time/marti/AL092004/webManager/displayGifsBy12hr_20.html

and

http://cimss.ssec.wisc.edu/tropic/real-time/marti/AL092004/webManager/displayGifsBy12hr_21.html

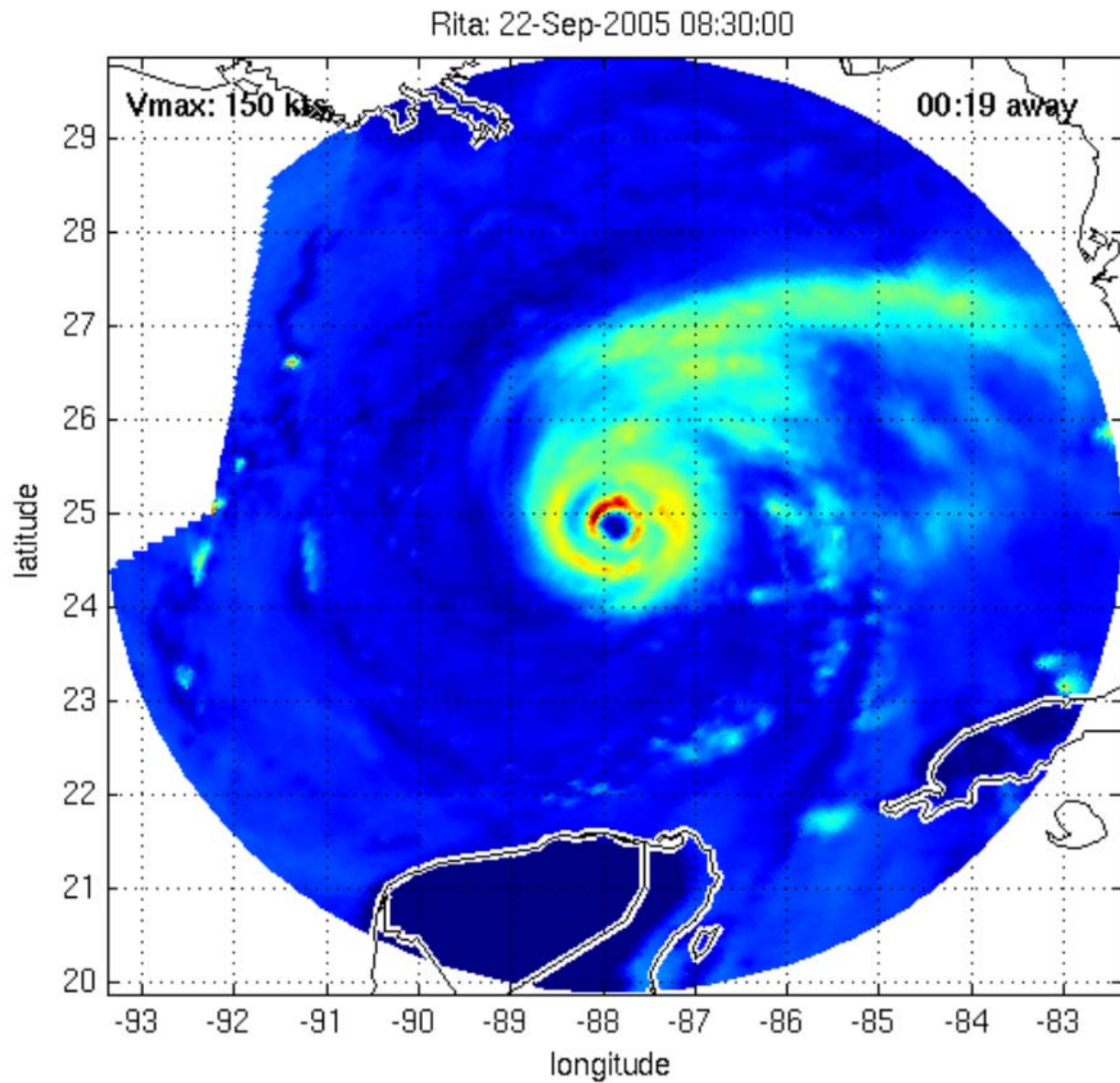
Hurricane Wilma, 2005



Microwave MIMIC satellite imagery of powerful Hurricane Wilma pounding Cancun MX while the inner eyewall and eye cross Cozumel Island (2:30 am CDT, 21 October 2005). Wilma, a category 4 hurricane at landfall, relentlessly assaulted these northeast Yucatan resorts for over 24 hours, before heading for southern Florida. Earlier, Wilma became the most intense hurricane ever recorded in the Western Hemisphere while over the Northwest Caribbean Sea.

Loop video available at: http://cimss.ssec.wisc.edu/tropic/real-time/marti/2005_TWENTY-FOUR/webManager/displayGifsBy12hr_07.html

Hurricane Rita (2005)



Microwave MIMIC satellite imagery of intense Hurricane Rita displaying concentric double eyewall structure over the central Gulf of Mexico (3:30 am, 22 September 2005).

Loop video viewable at:

http://cimss.ssec.wisc.edu/tropic/real-time/marti/2005_EIGHTEEN/webManager/displayGifsBy12hr_09.html