Scientist's Notebook

A look at space science research under way

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Seeking new insight on hurricanes

Scientists analyze immense data haul from CAMEX-3

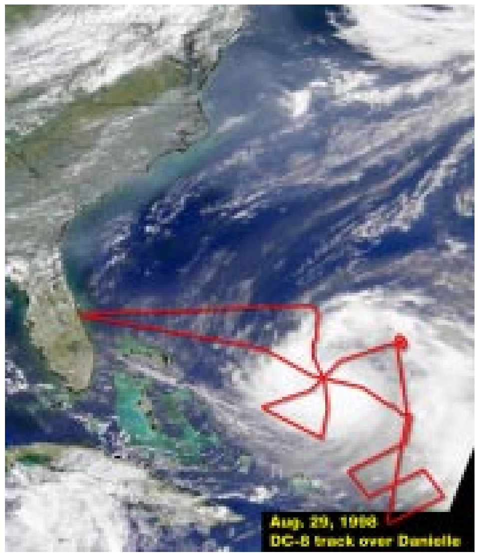
An eye that winked, a rain of ice crystals, and striking lightning show that hurricanes lead more complex lives than anyone had suspected. More details — and fuller understanding — will come in the next year as scientists analyze thousands of hours of data collected during the most comprehensive hurricane study project ever conducted.

"Although these opportunities do not provide immediate comfort to those who directly experienced this season's devastating storms," said Robbie Hood of NASA's Marshall Space Flight Center. "The wealth of information collected by all the agencies will lead to better hurricane forecast capabilities in the future."

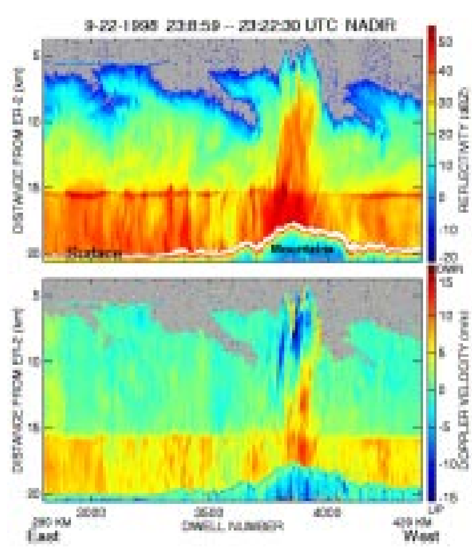
Hood was the lead mission scientist on the third Convection and Moisture Experiment (CAMEX-3), an ambitious project that brought together researchers from NASA, the National Oceanic and Atmospheric Administration, and the U.S. Air Force Reserve, and their associates in universities and the weather industry.

"The real success of CAMEX-3 was the breadth of hurricane information collected," said Ramesh Kakar, program manager at NASA Headquarters. "The combination of scientists from eight NASA centers, and the multi-agency, multi-university teamwork of CAMEX-3 was a tremendous example for the nation."

Kakar cited the assistance to NASA from numerous universities, the pilots and crews from Dryden Flight Research Center, and the project management staff from the Ames Research Center as keys to the success of CAMEX. "We are very grateful for the advice and coordination efforts of the National Oceanic and Atmospheric, and the support from the Air Force Reserve 53rd Weather Squadron, and the help from Federal Aviation Administration allowed the CAMEX-3 investigators to capitalize on key research opportunities when they arose."



The Aug. 29 flight path of NASA's DC-8 Airborne Laboratory is traced over a satellite image of Hurricane Danielle. NASA's DC-8 and ER-2 made numerous flights around and through several hurricanes and storms and returned a wealth of data like the radar views below, taken Sept. 22 as Hurricane Georges swept over Hispaniola. The ER-2 Doppler radar provided a dramatic cross-section view of Georges' eye, as the Dominican Republic received heavy rain (upper image). Subsequent rain caused significant loss of life. Rainfall apparently was significant when the 2.7 km-high (9000 ft) interior mountains produced what appears to be a huge thunderstorm over the mountains as shown in the blue — rising — moisture (lower image). (NASA)



Probing high for answers

Although meteorologists have been observing hurricanes for decades, some mysteries remain. Scientists can predict where hurricanes will go in the next 24 to 48 hours, but remain uncertain of how much strength a hurricane will gain, or exactly how it will change when it makes landfall.

Part of the answer lies at high altitudes, two to three times higher than NOAA and Air Force aircraft that routinely scout hurricanes, and inside the cloud tops which weather satellite cameras cannot penetrate.

The first two CAMEX campaigns were smaller NASA efforts. For CAMEX-3, NASA approached NOAA about coordinating with NOAA's regular hurricane reconnaissance flights so that larger data sets could be collected.

"We felt like NASA had something to contribute by providing remote sensing experience to the other agencies," Hood said.

At the core of CAMEX-3 were two NASA aircraft, its DC-8 Airborne Laboratory equipped with wind-sounding lasers, lightning sensors, radar, and other instruments, and an ER-2 high-altitude jet with lightning, radar and microwave sensors.

Teamwork

Where possible, the NASA flights were coordinated with NOAA's two WP-3D Orion patrol aircraft and a Gulfstream jet. NASA will also use data collected by the Air Force Reserve 53rd Weather Squadron's WC-130 Hercules Hurricane Hunters.

In addition, NASA employed its weather station on Andros Island in the Bahamas, and the Tropical Rainfall Measuring Mission (TRMM) satellite.

NASA aircraft used in CAMEX-3 were the ER-2, a single-seat, high-altitude research jet (top) and the DC-8 Airborne Laboratory (below), a converted jetliner with room for several scientists and their equipment (bottom). (NASA)

Hood said the team was not sure what would happen during the Aug. 12-Sept. 23 period set aside for CAMEX-3.

What they got were four major hurricanes — Bonnie, Danielle, Earl, and Georges — and a tropical storm — Hermine.

"Each of the hurricanes we sampled was different, so we think that was a great accomplishment to get so much different data," Hood said. "These kinds of data at these altitudes have not be collected before as a body."

The CAMEX-3 team now has more than 132 flight hours of data, which translates into several thousand hours of observations by the more than 30 instruments carried by the many aircraft or deployed into the storms.

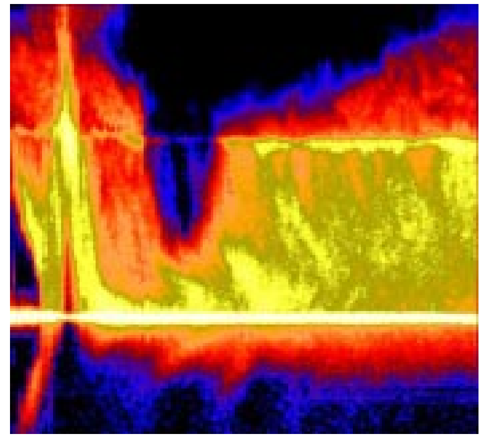
The analysis will take several months as scientists study their own data then confer with each other to understand.

Meanwhile, a number of early findings are emerging.

Complex answers

"The inflow and outflow wind patterns were much more complicated than we expected," Hood said. The direction and strength of the wind patterns are a measure of the energy flow within the hurricane, and and may help predict its future activities.

The best sights of the campaign was reserved for ER-2 pilot Dee Porter as he flew over hurricane Georges over the island of Hispaniola, in what Hood



This image by the Airborne Rain Mapping Radar (ARMAR) on the DC-8 shows shows a vertical slice through the northern eyewall of Hurricane Bonnie on Aug. 24. The slice is 65 km (40 mi) along the ground and 9 km (5.6 mi) up from the ocean surface (the white line; the below-surface image is a mirror-image return). The most intense precipitation, yellow and white at left, is the eyewall. Additional, less intense rain can be seen to the right (north) of the eyewall. In addition to the rain in the lower portion of the image, the ARMAR also sees ice-phase precipitation at higher altitudes (above about 5 km [3 mi]). The signal from ice particles is less strong than from liquid precipitation (rain) and is shown in red. The ice-phase particles are most likely aggregates (*i.e.*, snow), which is typical at higher levels in storms even in the tropics. Also, to the left of center is a gap, or area of weak signal, can be seen between the eyewall and the rain to the right. Hurricanes typically have rain organized into spiral bands with gaps between bands. (NASA)

Hurricanes are immense, natural heat engines at work

Sunlight heats the Eastern Atlantic Ocean. Water evaporates, rises, and forms rain, surrendering its heat to the air and accelerating the rise. Air flows in on the surface to replace rising air, barometric pressure drops, air masses slowly start circling.

The tropical depression becomes a tropical storm, winds grow until they pass the 110-km/h (60-knot) mark and keep rising, perhaps reaching 368 km/h (200 knots) or more. A hurricane is born, and becomes the focal point for meteorologists and disaster management experts.

Hurricanes are cyclonic storms whose power becomes greater toward the center, like water swirling ever faster down a drain. The winds are greatest at the core where they shear away to leave a calm "eye." (Typhoon is the name given cyclonic storms in the North Pacific Ocean. Tornadoes sometimes are called cyclones, but they are as different from hurricanes as a jazz dancer and a sumo wrestler.)

On average, hurricanes are no more powerful than ever. But more people live in coastal regions, and they have built more homes and businesses for hurricanes to destroy. So, the need to understand the mechanics of hurricanes increases each year as human populations grow in coastal areas.

As it aims for the Bahama Islands and the United States, Hurricane Bonnie displays the pinwheel pattern that is classic of cyclobic storm systems. (NASA)

"Intensity is the big thing," said CAMEX-3 Lead Mission Scientist Robbie Hood. "The hurricane community has made great strides in making more accurate forecasts. But how intense that hurricane's going to be when it hits the shoreline — or why some storms die out and others just keep going and going — is the important factor."

It all comes down to thermodynamics, the physics of heat. Water absorbs energy from the air or sunlight when it goes from sea surface to vapor, and surrenders energy to the air when it turns from vapor to rain drops.

Where the energy changes hands is what powers the hurricane, pumping up the winds which ultimately do most of the damage either directly or by driving waves ashore to form a storm surge.

To measure that energy exchange in seemingly clear air as well as in clouds, NASA will take a different look than hurricane hunters normally take.

"The big thing is that we're flying at higher altitudes than the other agencies normally fly," Hood said. "Routine flights at these altitudes haven't been done in the Atlantic since the 1950s. The DC-8 and the ER-2 each have done it once out in the Pacific, but no one had focused on Atlantic hurricanes."

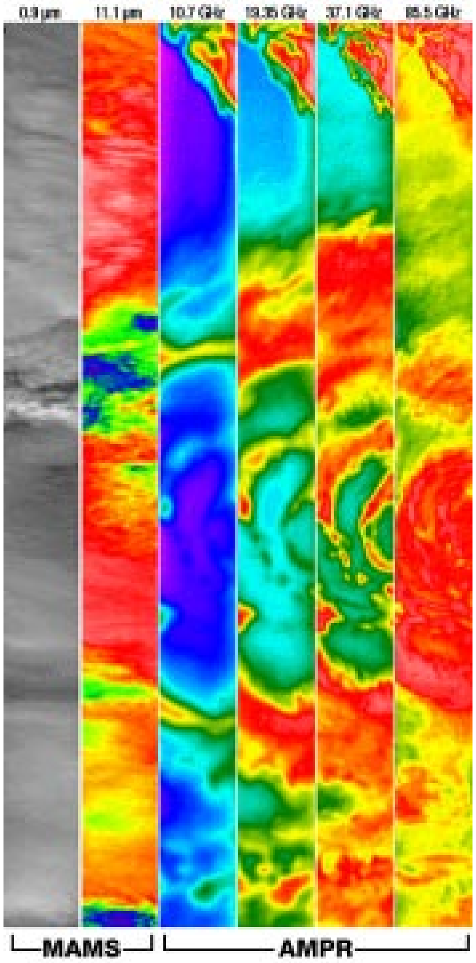
CAMEX-3 and TEFLUN-B

The third Convection And Moisture EXperiment (CAMEX-3) was a series of field research investigations sponsored by Dr. Ramesh Kakar, program manager for Atmospheric Dynamics and Remote Sensing at NASA Headquarters. The overall goal of CAMEX is to study atmospheric water vapor and precipitation processes using a unique array of aircraft, balloon, and land-based remote sensors. The first two CAMEX field studies were conducted at Wallops Island, VA, during 1993 and 1995.

CAMEX-3 was held Aug. 13-Sept. 23, 1998. This field campaign was devoted to the study of hurricane tracking and intensification using NASA-funded aircraft remote sensing instrumentation. The NASA ER-2 and DC-8 were the primary aircraft platforms used in the deployment; however, collaborations with the National Weather Service/Tropical Prediction Center/National Hurricane Center and National Oceanic and Atmospheric Administration/Hurricane Research Division were developed so that actual mission sorties involved as many as five to six aircraft.

The remote sensing instrumentation utilized by NASA during CAMEX-3 yielded high spatial and temporal information of hurricane structure, dynamics, and motion. These data, when analyzed within the context of more traditional aircraft, satellite, and ground-based radar observations, should provide additional insight to hurricane modelers and forecasters who continually strive to improve hurricane predictions. The ultimate goal of CAMEX-3 is to provide information which could someday assist in decreasing the size of coastal evacuation areas and increasing the warning time for those areas.

Many of the CAMEX-3 activities were combined with the second TExas and FLorida UNderflights Experiment (TEFLUN-B), which has complementary objectives. TEFLUN is a mission to obtain validation measurements for the Tropical Rain Measuring Mission (TRMM), developed by NASA and the National Space Development Agency of Japan. TRMM was launched Nov. 29, 1997. TEFLUN uses a combination of airborne and surface-based measurements to complement the satellite data. TRMM, *in situ* aircraft data, surface-based measurements, and computer models, will make unique contributions to our understanding of the tropical precipitation spectrum.



A series of images depicts a section of Bonnie as seen by the Multispectral Atmospheric Mapping Sensor (MAMS, strips 1 and 2) and the Advanced Microwave Precipitation Radiometer (AMPR, strips 4-6) carried by the ER-2 over Hurricane Bonnie on August 26, 1998. These depict cloud cover and cold cloud tops in visible and infrared light, and rainfall and ice distribution as seen in microwave bands. (NASA)

called "the most significant lightning measurements during the entire campaign." As Georges stomped across Hispaniola, the island's 2.7 km (9000 ft) mountain range caused a large bump to form in the middle of the storm.

"The clouds went down like a moat and came up like a wedding cake, and the ring around the cake was filled with lightning," she continued. "The pilot was pretty impressed." He also reported seeing reddish purple lightning jets rising from the cloud tops and seemingly reaching for space.

"The amazing thing about this data from (Hurricane) Georges is that the rain is enhanced significantly by the mountains in the interior of the Dominican

CAMEX team

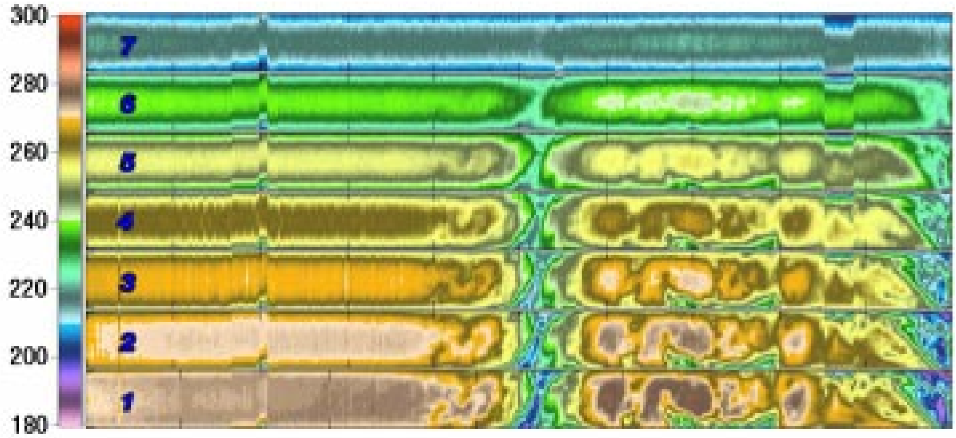
NASA centers: NASA Headquarters, mes Research Center, Dryden Flight Research Center, George C. Marshall Space Flight Center (including the Global Hydrology and Climate Center), Goddard Space Flight Center (including Wallops Flight Center), Jet Propulsion Laboratory, Langley Research Center.

Other organizations: National Oceanic and Atmospheric Administration (Atlantic Oceanographic and Meteorological Laboratory and Hurricane Research Division); Florida State University, Massachusetts Institute of Technology, Texas A&M University, University of Maryland - Baltimore County, University of Wisconsin - Madison; Desert Research Institute, Simpson Weather Associates.

Combined CAMEX-3/TEFLUN Flight Summary

August	
13	**TEFLUN B**: Deep convection measurements over Melbourne, FL, area. The TEFLUN-B ground coordination flight seems to be a large success. All three aircraft were in stacked formation, on coordinated lines, through an active storm, instruments working well, with a TRMM satellite overpass.
15	**TEFLUN B**: Deep convection measurements over central Florida
20	**TEFLUN B**: Convection east of Cape Canaveral. The DC-8 and UND Citation accomplished major goals in the stratiform rain environment while the TRMM satellite passed overhead.
21	**CAMEX-3**: Tropical Storm Bonnie synoptic flow measurements by the DC-8.
22	**TEFLUN B**: Citation II TEFLUN mission was successful.
23	**CAMEX-3**: Hurricane Bonnie eye wall #1. DC-8 and ER-2 made extremely successful flights over the eye wall of hurricane Bonnie in coordination with the NOAA aircraft. They both overflew the Andros Island site on the return from Bonnie.
24	**CAMEX-3**: Hurricane Bonnie eye wall #2. CAMEX bagged another highly successful overflight of Hurricane Bonnie in conjunction with the NOAA WP-3D Orion aircraft.
26	**CAMEX-3**: Hurricane Bonnie landfall. Another extremely successful flight day. Both ER-2 and DC-8 overflew Bonnie as it made landfall. There were three TRMM overpasses during the flight with the earliest overpass almost directly over the eye wall. Both NOAA WP-3D Orions also flew coordinated patterns with the NASA aircraft.
27	**TEFLUN B**: University of North Dakota Citation II (carrying cloud and rain particle sensors) had a successful flight studying convection over the National Center for Atmospheric Research (NCAR) S-band polarization radar (S-POL).
29	**CAMEX-3**: Hurricane Danielle. Vortex motion and evolution and moisture inflow measurements by DC-8.
30	**CAMEX-3**: Hurricane Danielle. Vortex motion and evolution and moisture inflow measurements by DC-8.
September	
2	**CAMEX-3**: DC-8 and ER-2 fly through the rain bands of Hurricane Earl.
5	**TEFLUN B**: TEFLUN flights studying stratiform rain
6	**TEFLUN B**: TEFLUN flights studying stratiform rain
8	**TEFLUN B**: ER-2 and Citation flew developing convection over SPOL for 3 hours, 25 minutes.
14	**TEFLUN B**: The DC-8 and Citation flew over convective cells just off the coast of the Cape.
15	**TEFLUN B**: The DC-8 and Citation flew their last coordinated TEFLUN mission for this experiment.
17	**TEFLUN B**: ER-2 and DC-8 make an excellent study of good convective lines and large stratiform regions.
21	**CAMEX-3**: Hurricane Georges. Successful eye wall flight into Georges.
22	**CAMEX-3**: Hurricane Georges. Successful synoptic inflow mission around Georges.

Note: Because of winds and other operational factors, not all aircraft flew every mission.



This image depicts temperatures (in degrees K) inside Hurricane Bonnie as seen in the 115-123 GHz microwave band as the ER-2 flew over on Aug. 26, 1998. The observations were made by the NPOESS Aircraft Sounder Testbed-Microwave Temperature Sounder (NAST-MTS). The channels shown are numbered in order of altitude (1 is the most transparent). The highest channel (7) shows upper-troposphere warming over the center of the hurricane, and the lower-altitude channels show increasingly intense temperature perturbations from the rainbands. NAST-MTS contains two microwave radiometer systems covering two frequency ranges. The 115-123 GHz band is centered on the 118.75 GHz oxygen line. (NASA)

Republic," said Gerry Heymsfield of NASA's Goddard Space Flight Center. "We got a glimpse of an example of the impact of the storms with a mountainous island and the subsequent rain which eventually caused significant loss of life. Understanding this very complicated interaction between Hurricane Georges and the mountains will keep us busy for a while."

In the wink of an eye

Another surprise came when hurricane Bonnie "winked" at the research team.

During successive passes by the DC-8 on Aug. 24, Bonnie's eye changed shape.

"I had no idea that the position or structure of the eye would change that fast," Hood said. "It was pulsating, it was undulating."

Storms are more than clouds; winds in clear air play a major role, so CAMEX-3 employed two laser sounding instruments to probe the hurricanes.

The MACAWS Doppler laser — which uses laser light like a police radar to measure speed — measured winds in the clear regions between cloud decks and in the eyes.

Laser scanners

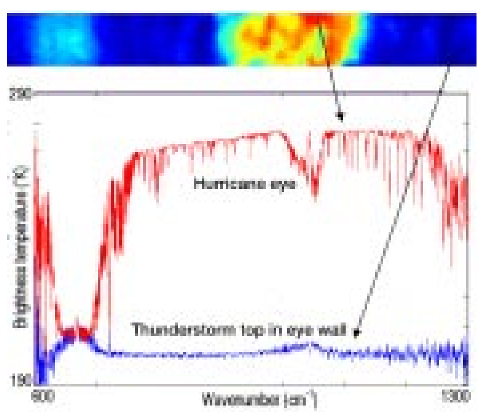
"These are the first wind measurements made in the eye wall of a hurricane with Doppler lidar [laser radar]," explained Jeffry Rothermel of the GHCC.

The LASE from NASA's Langley Research Center used its laser in a different manner, to measure water vapor and aerosols (suspended particles), also in clear air.

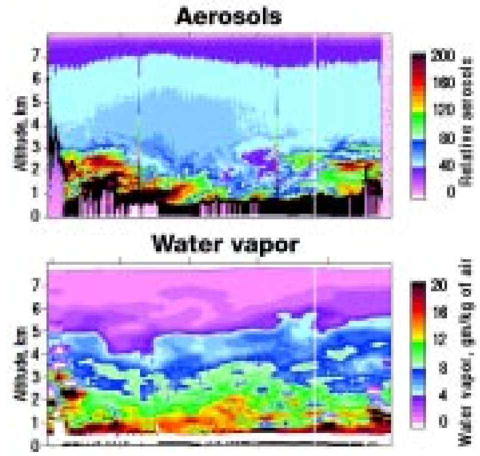
When the DC-8 flew southeast of Hurricane Bonnie on August 26, 1998 just before the storm hit the east coast of the U.S., LASE showed high concentrations of water vapor streaming into the hurricane. These LASE water vapor measurements will be used in numerical models to help understand the behavior of Hurricane Bonnie as it approached the coast.

LASE also measured water vapor profiles and aerosols as the DC-8 flew through the eye of Bonnie during brief cloud free periods. These are the first lidar measurements of water vapor inside the eye of a hurricane.

"CAMEX was successful on many different levels," Hood said. "We collected three-dimensional data sets on several storms, and we had good multiagency cooperation." ■



This plot illustrates the much colder cloud tops found in the eyewall in association with the thunderstorms compared to the relatively calm region of Bonnie's eye on Aug. 24. This image by the NPOESS Aircraft Sounder Testbed (NAST-I) depicts the infrared spectrum in two locations of the storm — the eye (in red) and in the eye wall (blue). (NASA)



The Lidar Atmospheric Sensing Experiment (LASE) made the first lidar measurements of water vapor inside the eye of a hurricane. LASE measured profiles of aerosols (upper) and water vapor (lower) when the DC-8 flew through the eye of Hurricane Bonnie on Aug. 26, 1998, just before the storm hit the east coast of the U.S. A broken cloud field was visually observed in Bonnie's eye. LASE measurements showed this eye to be quite large and revealed the precise altitudes of clouds within the eye. LASE also measured the vertical distribution of water vapor inside the eye of Bonnie during brief cloud free periods. LASE was mounted in the DC-8 Airborne Laboratory. (NASA)

Detailed descriptions of CAMEX-3 instruments and science, links to the science teams, and stories about daily operations are on line at:
http://ghrc.msfc.nasa.gov/camex3/

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