Overview of the Convection and Moisture Experiment (CAMEX)

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ABSTRACT

This paper presents an overview of the Convection and Moisture Experiment (CAMEX), including the field operations, aircraft platforms and missions, instrumentation, and data acquired during 1998 and 2001 field campaigns. A total of eight tropical storms and hurricanes were investigated during the CAMEX field campaigns including Bonnie, Danielle, Earl, and Georges during 1998 and Chantal, Erin, Gabrielle, and Humberto during 2001. Most of these storms were sampled with aircraft over the open ocean, but Hurricanes Bonnie (1998), Georges (1998), and Gabrielle (2001) also provided opportunities to monitor landfalling impacts. A few of the storms were sampled on multiple occasions during a course of several days. Most notable of these was Hurricane Humberto, which was sampled on three consecutive days during a cycle of both increasing and decreasing intensity change. Information collected for each of the eight CAMEX tropical storms as well as the Tropical Rainfall Measuring Mission validation activities are accessible via the CAMEX Web site and archived at the National Aeronautics and Space Administration Marshall Space Flight Center.

1. Introduction

The National Aeronautics and Space Administration (NASA) supports research that uses space-based observations to develop a better understanding of the earth system in order to improve the prediction of climate, weather, and natural hazards. Airborne and ground-based field experiments play a role in this kind of research because they offer opportunities to examine the accuracy of physical processes observed by satellites, to develop better understanding of physical processes so that improved parameterizations or data assimilation methods may be incorporated into predictive models utilizing satellite products, and to test new technologies that might be used in future satellite sensors.

The Convection and Moisture Experiment (CAMEX) is one such investigation sponsored by NASA to support satellite product validation, improved modeling, and technological development activities pertaining to spaceborne observations of atmospheric moisture. In preparation for the 1997 launch of the Tropical Rainfall Measuring Mission (Kummerow et al. 2000), two aircraft and ground-based field experiments were conducted in 1993 and 1995 at the NASA Wallops Flight Facility in Wallops Island, Virginia. The experiments were designed to test the performance of airborne and surface-based instrumentation that would later be used to support postlaunch validation of Tropical Rainfall Measuring Mission (TRMM) rainfall products. Instrumentation included active (radars and lidars) and passive (radiometers, interferometers, electric field mills) remote sensors, and radiosondes.

Validation of the basic TRMM oceanic and land rainfall products were the objective of a separate series of field experiments conducted in Florida, Brazil, and Kwajalein during 1998 and 1999 using many of the CAMEX instruments (Kummerow et al. 2000; Petersen et al. 2002; Houze et al. 2004; Sobel et al. 2004). The objective of CAMEX was then refocused in 1998 from a study of atmospheric moisture to a comprehensive study of tropical cyclones. This redirection was done in part to take advantage of the unique precipitation observational capabilities that TRMM offered for tropical

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cyclone monitoring, such as the vertical precipitation profiling capability of the TRMM precipitation radar. The new goal of CAMEX was to explore how forecasts of tropical cyclone intensity change, motion, rainfall potential, and landfalling impacts might be improved by spaceborne observations, data assimilation, and modeling.

Collaborative partnerships were developed with the Hurricane Research Division (HRD) of the National Oceanic and Atmospheric Administration (NOAA) Atlantic Oceanographic and Meteorological Laboratory and the United States Weather Research Program (USWRP) who have similar goals. The NOAA HRD annually investigates hurricanes with research aircraft as a major activity in a research portfolio seeking to improve the physical understanding and forecasting of hurricanes (for further information see http://www.aoml.noaa.gov/hrd). The USWRP is a multiagency program seeking to expedite the transfer of research advancements to the operational weather forecasting community with hurricanes at landfall being a major concern (Marks and Shay 1998; Elsberry and Marks 1999; Elsberry 2002).

Airborne and ground-based field experiments remained a priority activity during CAMEX in order to examine how well the physical processes affecting tropical cyclone behavior are observed by satellites, how better parameterizations of such quantities as hydrometeor microphysics or data assimilation of remotely sensed atmospheric moisture observations might improve the performance of tropical cyclone predictive models, and how advances in remote sensing instrumentation might provide better tropical cyclone observational capabilities in the future. Two additional CAMEX field experiments were organized to examine tropical cyclones using spaceborne, airborne, and ground-based assets. These field campaigns were called CAMEX-3 and CAMEX-4, and were conducted in 1998 and 2001, respectively. Each experiment was based in Florida to allow easy aircraft access to the tropical cyclones in the western Atlantic Ocean basin and the Gulf of Mexico, and to provide closer coordination with the NOAA aircraft, which were also based in Florida. The early CAMEX sensors were incorporated into a larger, more complete collection of remote sensing and in situ instrumentation. Joint aircraft missions with NOAA HRD during CAMEX-3 and CAMEX-4 successfully sampled a total of eight tropical storms and hurricanes.

This special issue presents research results derived from the joint NASA and NOAA HRD partnership during CAMEX-3 and CAMEX-4. Contributing authors include CAMEX Science Team members and NOAA HRD personnel. These results encompass a wide variety of topics such as the effects of microphysical parameterizations on numerically simulated hurricanes, observational studies of highly sheared storms, or demonstration of new microwave remote sensing techniques and data products, to name just a few. The range of topics is so broad that a detailed summary of the results is beyond the scope of this paper. Instead, the goal of this paper is to present an overview of the CAMEX-3 and CAMEX-4 field campaigns and to provide reference material and context for the discussion of the scientific findings in the accompanying articles in this special issue. Included in this paper are descriptions of the field operations, aircraft platforms and missions, instrumentation, and data acquired. CAMEX-3 is discussed in section 2 and CAMEX-4 is discussed in section 3. The CAMEX data archive and access procedures are presented in section 4, while section 5 contains the concluding remarks.

2. CAMEX-3

The NASA Earth Science Enterprise (reorganized in 2004 into the NASA Science Mission Directorate) and the NOAA HRD began an informal collaboration during the 1998 field operations of CAMEX-3. NASA assembled a unique array of remote sensing and in situ aircraft instrumentation for the high altitude ER-2 and the medium altitude DC-8 aircraft along with ground-based radar, profiler, and radiosonde resources. These assets were highly complementary to those of the NOAA WP-3D Orion (P-3) aircraft (Jorgensen 1984), which carried instrumentation such as flight-level sensors, radars, radiometers, cloud physics instrumentation, and expendables such as dropsondes, ocean probes, and drifting buoys. The CAMEX and NOAA HRD scientists developed joint research strategies to investigate the interplay of hurricane inner core dynamics with the upper tropospheric environment, to study the relationship of the synoptic flow environment to hurricane tracking and intensity change, to explore parameters pertinent to improving quantitative precipitation forecasting of landfalling hurricanes, and to sample the environment of potential hurricane genesis conditions. Based on these strategies, the NASA and NOAA aircraft collected joint datasets when targets of opportunities were present that satisfied the research objectives of both groups. The NASA/NOAA aircraft missions proved to be a highly successful endeavor that provided three-dimensional sampling of hurricane conditions with the NASA aircraft focusing on altitudes above 9 km, while the NOAA aircraft concentrated on altitudes in the vicinity of 4–6 km.

a. CAMEX-3 field operations

The CAMEX-3 field phase was based in central Florida, with NASA aircraft at Patrick Air Force Base (AFB) and NOAA aircraft at MacDill AFB. In conjunction with the airborne observations, a ground-based validation site was established on Andros Island, Bahamas. Using rawinsondes, a lidar, and a radiance interferometer, the ground validation team made regular observations providing vertical retrievals of temperature, humidity, winds, and water vapor profiles (Table 1). The CAMEX-3 field experiment ran from 8 August to 27 September 1998 and conducted operations in hurricanes Bonnie, Danielle, Earl, and Georges (Fig. 1).

In addition to the CAMEX airborne and surface field operations, the Texas and Florida Underflights Experiment (TEFLUN), a parallel NASA field experiment in central Florida, provided additional ground validation observations (Datta et al. 2003; Durden et al. 2003a). TEFLUN-B, the second of its kind, was a Tropical Rainfall Measuring Mission precipitation experiment designed to obtain airborne and surface measurements needed to validate the TRMM rainfall algorithms. A dense TEFLUN-B rain gauge and disdrometer network was located in central Florida during August and September 1998. TEFLUN-B also deployed the National Center for Atmospheric Research S-band polarization radar, the NOAA Aeronomy Laboratory Profiler system and coordinated closely with the Melbourne, Florida, Weather Surveillance Radar-1988 Doppler (WSR-88D), and CAMEX-3 field team (Habib and Krajewski 2002).

b. Aircraft platforms and instrumentation

The goals of the NASA aircraft used during CAMEX-3 were to provide high spatial and temporal information of the tropical cyclone structure, dynamics, and motion using both remote sensing and in situ sampling methods. The NASA ER-2 and DC-8 aircraft were the primary CAMEX airborne platforms (NASA Facts 2002a; NASA Facts 2002b). Both aircraft typically flew missions between 5 and 8 h in length depending upon the science objective, flight pattern, and location of the tropical cyclone relative to Patrick AFB. Most missions were conducted within an 1800-km radius of Patrick AFB. The CAMEX Science Team chose this distance because it was considered the best compromise between sampling time and transit time. All missions were coordinated with the Federal Aviation Administration and the Chief, Aerial Reconnaissance Coordination, All Hurricanes (CARCAH) located at the NOAA National Hurricane Center to ensure the CAMEX aircraft did not interfere with commercial traffic or hurricane reconnaissance aircraft operations.

The NASA ER-2 aircraft served as the high-altitude platform typically flying at an altitude of approximately 20 km (Table 2). The ER-2 aircraft sampled the environment in the upper altitude regions of the hurricane not normally observed by either research or operational weather reconnaissance aircraft. At altitude, the ER-2 flew above the hurricane convection. The airplane was generally unaffected by in situ clouds but did experience occasional turbulence over areas of intense updrafts. The CAMEX instrumentation aboard the ER-2 was carried within four large pressurized fuselage experiment compartments: a nose compartment, instrument pods suspended from each wing, and one under the fuselage. Table 1 lists the ER-2 research instrumentation consisting mainly of remote sensors.

The NASA DC-8 aircraft served as the medium altitude platform. The DC-8 is a four-engine commercial jet that has been modified to carry up to 13 000 kg of scientific instruments and equipment (Tables 1 and 2). During the CAMEX hurricane missions, the DC-8 typically flew at altitudes between 11.5 and 12.8 km. Depending on the mission objectives and sampling strategies, the DC-8 missions occasionally included repeated flight legs at stair-stepped altitudes or spiral descent maneuvers to conduct microphysical and other in situ sampling. Most DC-8 missions were coordinated with the NASA ER-2 flying above. The DC-8 features included wing instrument pylons, a dropsonde delivery tube, atmospheric sampling probes, and several reinforced ports that allowed instrumentation to point in virtually any direction. The DC-8 onboard support facilities included an integrated navigation management system, a satellite-based time code generator, a standalone global positioning system, and a weather satellite receiver system. Table 1 also lists the DC-8 research instrumentation. This instrumentation included a mixture of remote sensors and in situ sampling devices.

NASA also funded the University of North Dakota (UND) to fly an instrumented Cessna Citation airplane during the TEFLUN-B precipitation missions. These missions typically involved the ER-2 at high altitudes, the DC-8 aircraft flying at middle altitudes, and the UND Citation below with an extensive array of microphysical instruments (Stith et al. 2002).

In addition to the NASA aircraft, missions were flown jointly with the NOAA P-3 research aircraft when mutual scientific objectives existed between the CAMEX and NOAA HRD science teams. During CAMEX-3 the NOAA P-3 typically flew in the altitude range of 6.0–7.0 km. Additional aircraft flight specifications are listed in Table 2 (also available at

TABLE 1. Research instruments deployed during CAMEX-3.

Instrument	Principal investigator	Sensor type	Description of parameters measured	Platform
Atmospheric emitted radiance interferometer	R. Knuteson/University of Wisconsin—Madison	Michelson interferometer	Planetary boundary layer temperature and moisture profiles	Andros Island
Rawinsonde	F. Schmidlin/NASA	Radiosonde with GPS navigation	Atmospheric pressure, temperature, humidity, and winds	Andros Island
Goddard Space Flight Center scanning Raman lidar	D. Whiteman/NASA	XeF excimer laser and an Nd:YAG laser	Water vapor and aerosols	Andros Island
Advanced Microwave Precipitation Radiometer	R. Hood/NASA	Scanning radiometer	Precipitation and surface water	ER-2
ER-2 Doppler radar	G. Heymsfield/NASA	Doppler radar 9.6 GHz	Vertical structure of precipitation and air motions	ER-2
Lightning instrument package	R. Blakeslee/NASA	Electric field mill and conductivity	Lightning, electric fields, and electric field changes	ER-2
Multispectral atmospheric mapping sensor	A. Guillory/NASA	Scanning visible and infrared	Total column water vapor, sea and land surface temperatures	ER-2
Millimeter imaging radiometer	J. Wang/NASA	Scanning radiometer	Water vapor and temperature profiles	ER-2
National Polar-Orbiting Operational Environmental Satellite System (NPOESS) aircraft sounder testbed imager	W. Smith/NASA	High-resolution infrared interferometer	Surface temperature, atmospheric temperature, and water vapor content	ER-2
NPOESS aircraft sounder testbed microwave temperature sounder	P. Rosenkranz/Massachusetts Institute of Technology	Scanning microwave sounder	Atmospheric temperatures; 17 channels in the vicinity of 54, 118 GHz	ER-2
Airborne multichannel microwave radiometer	J. Wang/NASA	Microwave radiometer	Water vapor and precipitation	DC-8
Airborne rain mapping radar	S. Durden/Jet Propulsion Laboratory (JPL)	Doppler radar 13.8 GHz	Vertical structure of precipitation	DC-8
Airborne vertical atmosphere profiler	J. Halverson/University of Maryland, Baltimore County	Dropsonde	Vertical profile of atmospheric temperature, pressure, relative humidity, and wind speed	DC-8
Cloud and aerosol particle characterization	R. Pueschel/NASA	Laser optical particle counter	Growth of cloud drops and ice crystals through aggregation, riming, and coalescence	DC-8
DC-8 meteorological aircraft	P. Bui/NASA	Rosemont probes	In situ temperature, pressure, and wind field	DC-8
Measuring system JPL laser hygrometer	R. Herman/JPL	Hygrometer	Water vapor volume and mixing ratio	DC-8
JPL standing acoustic wave hygrometer	M. Hoenck/JPL	Hygrometer	Dewpoint	DC-8
Lightning instrument package	R. Blakeslee/NASA	Electric field mills and conductivity	Lightning, electric fields, and electric field changes	DC-8
Multicenter airborne coherent atmospheric wind sensor	J. Rothermel/NASA	Lidar	Two-dimensional wind fields and vertical profiles	DC-8
Polar scanning radiometer	A. Gasiewski/NOAA	Microwave imaging radiometer	Precipitation, water vapor, and surface water	DC-8

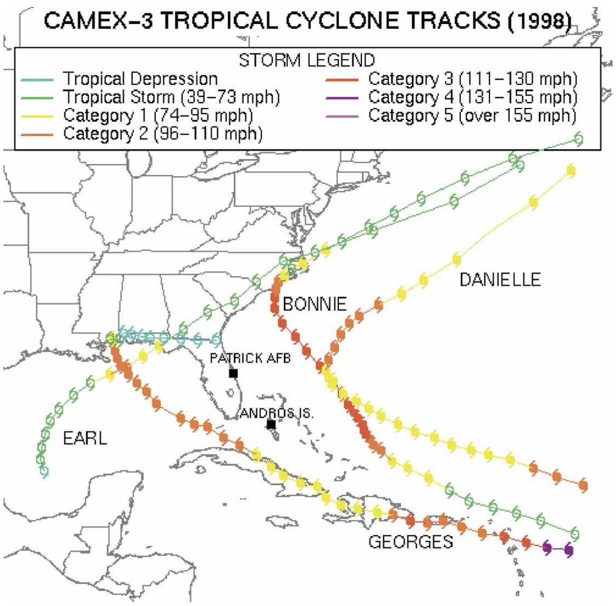

FIG. 1. Tracks of tropical cyclones flown during CAMEX-3.

http://www.aoml.noaa.gov/hrd/aircraft.html). The NASA missions also overlapped with those of the operational hurricane aircraft such as the NOAA Gulfstream-IV SP jet (G-IV) and C-130 operated by the 53rd Weather Reconnaissance Squadron of the United States Air Force Reserve. The NOAA G-IV, based at MacDill AFB near Tampa, Florida, is used to conduct operational synoptic surveillance missions in the environments of hurricanes. The G-IV flight characteristics (Table 2) are described in detail by Aberson and Franklin (1999). The C-130 aircraft were tasked by the NOAA National Hurricane Center, through CARCAH, to perform storm reconnaissance.

c. CAMEX-3 tropical cyclones and missions

The CAMEX-3 field experiment investigated four tropical cyclones (Table 3) as well as thunderstorms and stratiform precipitation in central Florida and the surrounding Gulf of Mexico and Atlantic Ocean regions (Figs. 2 and 3). Pasch et al. (2001) summarized the 1998 Atlantic hurricane season; however, a brief description of the tropical cyclones flown during CAMEX-3 follows. The first storm to be investigated was Bonnie, which transitioned from a tropical storm to a category 3 hurricane during 21–26 August 1998. On 21 August 1998, the DC-8 conducted a synoptic flow mission designed to characterize the environment ahead of then–Tropical Storm Bonnie. The next two missions utilized both the DC-8 and the ER-2 (23 and 24 August 1998) to sample Bonnie as a category 3 hurricane. These two missions were inner storm core studies that emphasized observations of the vortex dynamics of the eyewall. During these missions the DC-8 released a series of dropsondes to measure the vertical structure of the storm (Table 3). The final Hurricane Bonnie flight occurred on 26 August 1998 as the storm was beginning to make landfall near Wilmington, North Carolina. The NASA and NOAA P-3 aircraft both sampled the structural changes of the overocean portions of the storm as it began to interact with the land. The DC-8 and the ER-2 underflew the TRMM satellite on three successive overpasses in support of TRMM validation studies (Heymsfield et al. 2000).

The next CAMEX-3 aircraft missions flown by the DC-8 were into Hurricane Danielle on 29 and 30 August 1998. However, mechanical problems on the ER-2 limited it to a single shortened mission on 30 August 1998. The two DC-8 flights into Danielle were closely coordinated with both of the NOAA P-3s as part of a vortex motion and evolution flight pattern, which focused on the inner core dynamics through repeated radial penetrations of the hurricane eye. An additional NOAA goal for the 29 August 1998 flight was to densely sample Hurricane Danielle and its environment with dropsondes. NASA assisted in this effort by releasing NOAA dropsondes from the DC-8. A total of 40 dropsondes were deployed by the DC-8, in addition to those operationally deployed by the NOAA G-IV during its synoptic surveillance mission. The next DC-8 Danielle mission on 30 August 1998 studied the inner core storm structure and the storm inflow.

The third storm sampled was Hurricane Earl on 2 September 1998 by the ER-2, DC-8, and UND Citation (in coordination with the TEFLUN-B experiment). The CAMEX-3 objective was to study the convective and stratiform regions of the outer rainbands on the eastern side of Earl. Simultaneously, a NOAA P-3 flew a hurricane landfall mission with an additional science objective to map the storm surge along the Gulf Coast. The NOAA P-3 and the NASA DC-8 coordinated flight legs along radials between Eglin AFB and the Tallahassee WSR-88D radar site. At the time, Earl was

TABLE 2. CAMEX aircraft specifications.

Aircraft	Typical CAMEX altitude (km)	Cruising speed (m s^{-1})	Max range (km)	Max payload capacity (kg)
NASA ER-2	19.8	210	5555	1179
NASA DC-8	11.5–12.8	235	9258	13 000
NOAA P-3	6.0–7.0	170	6100	4090
NOAA G-IV	12.0–13.7	240	7400	2177
Aerosonde	<1.0	30	3000	5

TABLE 3. CAMEX-3 tropical cyclones and aircraft mission objectives.

Date	Storm name	Storm strength	Aircraft	Dropsondes	Primary mission objective
21 Aug 1998	Bonnie	Tropical storm	DC-8	1	Synoptic flow
23 Aug 1998	Bonnie	Category 3	DC-8, ER-2	10	Inner core dynamics
24 Aug 1998	Bonnie	Category 3	DC-8, ER-2	9	Inner core dynamics
26 Aug 1998	Bonnie	Category 3	DC-8, ER-2	7	Landfalling impacts/TRMM overpasses
29 Aug 1998	Danielle	Category 1	DC-8	40	Vortex motion and evolution experiment
30 Aug 1998	Danielle	Category 1	DC-8, ER-2 (ER-2 partial dataset)	8	Data assimilation/inner core dynamics
2 Sep 1998	Earl	Category 1	DC-8, ER-2, UND Citation	5	Rainbands/landfalling impacts
21 Sep 1998	Georges	Categories 2 and 3	DC-8, ER-2	5	Eyewall study
22 Sep 1998	Georges	Category 2	DC-8, ER-2	9	DC-8: synoptic flow ER-2: landfalling impacts
25 Sep 1998	Georges	Category 2	ER-2	N/A	Rainbands/landfalling impacts
27 Sep 1998	Georges	Category 2	ER-2	N/A	Rainbands/TRMM overpass

intensifying from a category 1 to a category 2 hurricane, as well as interacting with a shortwave trough and likely entraining dry air (Guillory et al. 2000). The storm produced some intense convection as it made landfall on the Florida coast.

Hurricane Georges was the final storm studied during CAMEX-3. The DC-8 gathered data on two occasions (21 and 22 September 1998) and the ER-2 on four missions (21, 22, 25, and 27 September 1998). The first Hurricane Georges mission was on 21 September 1998 near St. Croix, Virgin Islands, but because of the distance to reach the storm, the aircraft were limited to a short pattern to map the inner core of the storm.

The second flight was on 22 September 1998, while the storm was making landfall on the island of Hispaniola. This time Hurricane Georges was well within the aircraft range, thus permitting more time for storm research. The initial flight tracks for both the ER-2 and DC-8 crossed over the Dominican Republic. In the case of the DC-8 the primary focus of its mission was to study the inflow to the south, east, and north of the storm center, while the ER-2 focused on the intense convection and mapping the heavy orographically forced rainfall over the island of Hispaniola. One NOAA P-3 flew in the rainbands south of the island while the eye was over land. The convection had storm

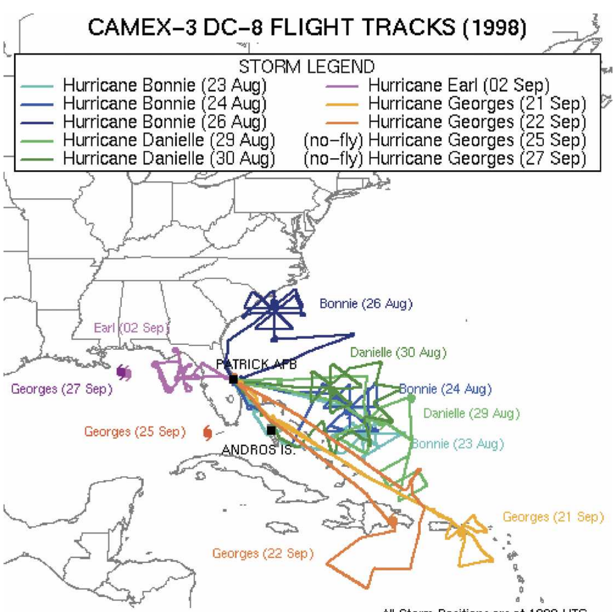

FIG. 2. Flight tracks of the NASA DC-8 over tropical cyclones flown during CAMEX-3.

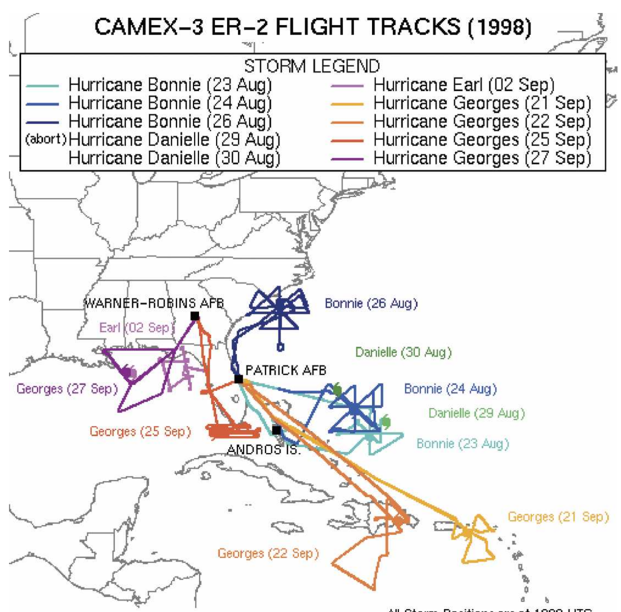

FIG. 3. Flight tracks of the NASA ER-2 over tropical cyclones flown during CAMEX-3.

top echoes exceeding 12 km and updrafts over 20 m s^{-1} (39 kt) at that altitude (Geerts et al. 2000). This mission represented the last science flight of the DC-8 during CAMEX-3 since it was deployed to another field campaign after 22 September 1998.

Following landfall on Hispaniola, the forecasted track for Hurricane Georges was to head up the Florida Peninsula. The threat of damaging winds at Patrick AFB necessitated an evacuation of the base where the CAMEX-3 aircraft were located. The ER-2 was redeployed to Warner-Robbins, Georgia, in order to continue observations of Georges. The ER-2 flight on 25 September 1998, out of Robbins AFB, focused on the rainbands as Georges made landfall in Key West, Florida, with maximum sustained winds of 46 m s^{-1} (89 kt). Although not closely coordinated with the ER-2, a NOAA P-3 flew Hurricane Georges on a reconnaissance flight at approximately the same time. The NOAA P-3 flight crew assisted CAMEX by providing navigational coordinates of the rainband locations to the ER-2 pilot.

The final ER-2 flight over Georges was along the Gulf Coast from Florida to Louisiana on 27 September 1998. This flight served dual purposes as a landfalling study of the storm's rainbands and as a TRMM validation mission with a satellite overpass. The ER-2 flew above the initial rainbands of Georges as they began crossing the shoreline. This mission was not coordinated with the NOAA P-3, which flew several hours later mapping the winds at landfall as the eye crossed the coastline. The Mobile Integrated Profiling System (MIPS) of the University of Alabama at Huntsville (UAH) was also deployed on the coast near Lymon, Mississippi. The MIPS instrumentation included a microwave profiler, sodar, ceilometer, and surface weather sensors.

3. CAMEX-4

A more formal collaboration was established between the NASA Earth Science Enterprise, the NOAA Hurricane Research Division, and the United States Weather Research Program during the CAMEX-4 field operations of 2001. The aircraft mission goals were designed to be mutually beneficial to each partner. One priority was collecting observations that could be used to validate model parameterizations and data assimilation techniques. Specifically, CAMEX-4 emphasized high spatial and temporal observations of tropical cyclone structure, dynamics, motion, and intensity change amid its surrounding environment. At least one NOAA P-3 aircraft accompanied the NASA aircraft on every priority science mission including auxiliary thunderstorm missions in the vicinity of Key West, Florida, as part of the Keys Area Microphysics Project (KAMP). These auxiliary missions supported the secondary CAMEX objective to study thunderstorm structure, precipitation systems, and atmospheric water vapor profiles in an effort to improve quantitative precipitation estimates.

a. CAMEX-4 field operations

The NASA airborne platforms used during CAMEX-4 included piloted aircraft and uninhabited aerial vehicles. The main CAMEX-4 field operation center was located at the Naval Air Station (NAS) in Jacksonville, Florida, where the piloted aircraft were deployed. This location enabled the NASA research aircraft to reach storms near Belize (i.e., Tropical Storm Chantal) and off the East Coast of the United States (Hurricane Erin, Tropical Storm Gabrielle, and Hurricane Humberto). The uninhabited aerial vehicles were deployed from the nearby Mayport Naval Station in Mayport, Florida.

The Jacksonville location also provided ready flight access to the Florida Keys where the KAMP surface validation network was established. The CAMEX portion of this network included the aforementioned UAH MIPS and four surface research radars (Table 4). NASA funded the placement of a rain gauge and disdrometer network at the same site to support validation of TRMM precipitation products (Tokay et al. 2003). The KAMP location was within 700 km of NAS Jacksonville and provided ample opportunities to study thunderstorm structure, precipitation systems, and atmospheric water vapor profiles with both passive and active microwave instruments aboard aircraft and complementary TRMM overflights.

b. Aircraft platforms and instrumentation

The primary CAMEX-4 aircraft that sampled the tropical cyclones were the NASA ER-2 and the DC-8. Many of the aircraft instruments deployed during CAMEX-3 were utilized again during CAMEX-4. Notable instrument additions included an ER-2 high-altitude dropsonde, which enabled dropsonde launches for the first time from a high-altitude airplane, and a more comprehensive array of microphysical sampling instruments than previously flown during CAMEX-3. The complete instrument manifest for the CAMEX-4 aircraft is contained in Table 4.

The airborne assets of CAMEX-4 also included four Aerosonde uninhabited aerial vehicles. The Aerosondes are miniature, robotic airplanes equipped to measure air temperature and humidity (i.e., a remote-

TABLE 4. Research instruments deployed during CAMEX-4.

Instrument	Principal investigator	Sensor type	Description of parameters measured	Platform
Rawinsonde	F. Schmidlin/NASA	Radiosonde with GPS navigation	Atmospheric pressure, temperature, humidity, and winds	Andros Island
Mobile integrated profiling system	K. Knupp/University of Alabama at Huntsville	Ceilometer, sodar, surface stations, electric field mill, and microwave profiling radiometer	Cloud-base heights, vertical motion, wind profiles, surface conditions, electric field magnitude, cloud liquid water, water vapor	KAMP
Tropical Oceans Global Atmosphere radar	J. Gerlach/NASA	C-band Doppler radar	Doppler velocity and radar reflectivity for derived rainfall rates	KAMP
NASA polarimetric S-band radar	J. Gerlach/NASA	S-band Doppler radar	Doppler velocity and radar reflectivity for derived rainfall rates	KAMP
Shared mobile atmosphere research and teaching radar	M. Biggerstaff/Texas A&M University	C-band Doppler radar	Doppler velocity and radar reflectivity for derived rainfall rates	KAMP
Mobile X-band polarimetric weather radar	E. Anagnostou/University of Connecticut	Dual-polarized X-band radar	Doppler velocity and radar reflectivity for derived rainfall rates	KAMP
Aerosonde	G. Holland/Aerosonde Corp and J. Curry/University of Colorado	Sonde	Temperature, humidity, wind speed, and surface conditions	Aerosonde
Advanced microwave precipitation radiometer	R. Hood/NASA	Scanning radiometer	Precipitation and surface water	ER-2
Dual-beam UV absorption ozone photometer	E. Richard/NOAA	In situ photometer	In situ ozone directly through ultraviolet light absorption	ER-2
ER-2 Doppler radar	G. Heymsfield/NASA	Doppler radar 9.6 GHz	Vertical structure of precipitation and air motions	ER-2
ER-2 high altitude dropsonde	J. Halverson/University Maryland, Baltimore County	Dropsonde	In situ vertical profile of temperature, pressure, relative humidity, and wind speed and direction	ER-2
High altitude Monolithic Microwave Integrated Circuit (MMIC) sounding radiometer	B. Lambrigsten/JPL	Radiometer	Temperature, humidity, and cloud liquid water sounding	ER-2
Lightning instrument package	R. Blakeslee/NASA	Electric field mills and conductivity	Lightning, electric fields, and electric field changes	ER-2
Lyman-alpha hygrometer	K. Kelly/NOAA	Hygrometer	Directly measures water vapor through sampling	ER-2
Microwave Temperature	M. J. Mahoney/JPL	Microwave radiometer	Atmospheric temperature	ER-2
Profiler Moderate Resolution Imaging Spectroradiometer (MODIS) Airborne Simulator (MAS)	J. Myers/NASA	Scanning multichannel spectrometer	High spatial resolution imagery of cloud and surface features	ER-2
Airborne vertical atmosphere profiler	J. Halverson/University Maryland, Baltimore County	Dropsonde	Vertical profile of atmospheric temperature, pressure, relative humidity, and wind speed	DC-8
Cloud microphysics suite	A. Heymsfield/NCAR	Spectrometer and probes	Cloud and aerosol particle size, distribution, and shape	DC-8
Conically scanning two-look airborne radiometer	R. Hood/NASA	Radiometer	Precipitation, surface water and near-ocean surface wind speed and direction	DC-8

TABLE 4. *(Continued)*

Instrument	Principal investigator	Sensor type	Description of parameters measured	Platform
Counterflow virtual impactor	A. Heymsfield/NCAR	Microphysics	Cloud ice and water content	DC-8
DC-8 meteorological measuring system	P. Bui/NASA	Rosemont probes	In situ temperature, pressure, and wind field	DC-8
JPL laser hygrometer	R. Herman/JPL	Hygrometer	Water vapor volume and mixing ratio	DC-8
Lidar atmospheric sensing experiment	E. Browell/NASA	Differential absorption lidar	Distribution of water vapor, aerosols and clouds throughout the troposphere	DC-8
Lightning instrument package	R. Blakeslee/NASA	Electric field mills and conductivity	Lightning, electric fields, and electric field changes	DC-8
Microwave temperature profiler	M. J. Mahoney/JPL	Microwave radiometer	Atmospheric temperature	DC-8
Nevzorov probe	A. Heymsfield/NCAR	Water vapor probe	Condensed water content and the total (condensed plus vapor) water content	DC-8
Precipitation radar-2d generation	E. Im/JPL	Radar	Rainfall rate, and vertical and horizontal atmospheric velocities	DC-8

controlled, flying radiosonde). These 13.5-kg planes typically flew 11-h missions at altitudes ranging from 15–1000 m (further information available online at http://www.aerosonde.com). During CAMEX-4, the Aerosondes flew eight individual sonde missions guided remotely from their Mayport Naval Station home base. The Aerosondes were equipped with lightweight video cameras to help researchers understand sea surface changes during tropical cyclones. The goal of the Aerosonde deployments during CAMEX-4 was to sample and measure the atmospheric boundary layer conditions and sea surface characteristics that influence the development and intensification of tropical cyclones. The Aerosondes were also outfitted with an onboard laser altimeter, which enabled the aircraft to fly as low as 40 m. The eight Aerosonde missions were flown between 19 August and 9 September 2001. The Aerosonde missions, just like those of the ER-2 and DC-8 aircraft, were coordinated with the Federal Aviation Administration and CARCAH to ensure no conflicts occurred with any of the operational hurricane aircraft. After the tragic events on 11 September 2001, the Aerosondes were not permitted to fly for the duration of CAMEX-4 since they were not equipped with a transponder to identify the aircraft.

c. *CAMEX-4 tropical cyclones and missions*

Four tropical cyclones (Table 5 and Fig. 4) were studied during CAMEX-4. The first of these was Tropical Storm Chantal on 20 August 2001. On this day, Chantal was gaining strength and was becoming more organized as the storm approached Belize and the Yucatan Peninsula. Maximum sustained winds speeds were estimated at 31 m s^{-1} (60 kt; Beven et al. 2003). The flights of the DC-8 (Fig. 5), ER-2 (Fig. 6), and NOAA P-3 aircraft were coordinated to emphasize quantitative precipitation estimation as a scientific objective. This mission focused on sampling the active rainbands and

TABLE 5. CAMEX-4 tropical cyclones and aircraft mission objectives.

Data	Storm name	Storm strength	Aircraft	Dropsondes	Primary mission objective
20 Aug 2001	Chantal	Tropical storm	DC-8, ER-2	7	Quantitative precipitation estimation
10 Sep 2001	Erin	Category 3	DC-8, ER-2	11	Data assimilation
15 Sep 2001	Gabrielle	Tropical storm	DC-8	9	Extratropical transition/inner core dynamics
16 Sep 2001	Gabrielle	Tropical storm	ER-2	N/A	Inner core dynamics
22 Sep 2001	Humberto	Tropical storm	DC-8, ER-2	14	Quantitative precipitation estimation
23 Sep 2001	Humberto	Categories 1 and 2	DC-8, ER-2	25	Coordinated Observations of Vortex Evolution and Structure (COVES)#1
24 Sep 2001	Humberto	Categories 1 and 2	DC-8, ER-2	23	Coordinated Observations of Vortex Evolution and Structure (COVES)#2

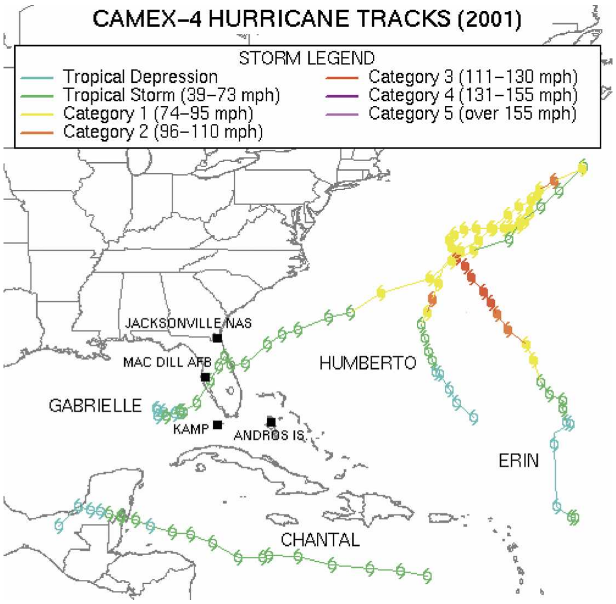

FIG. 4. Tracks of tropical cyclones flown during CAMEX-4.

eyewall with repeated legs along the most convective areas of precipitation. For this case, the flight legs near the center were intended to provide insight into storm intensity changes. The forecast for Chantal was for it to continue to strengthen into a more organized storm. Although the CAMEX aircraft experienced strong convection during the flight, Chantal soon made landfall on the Belize–Mexico border and never achieved hurricane status.

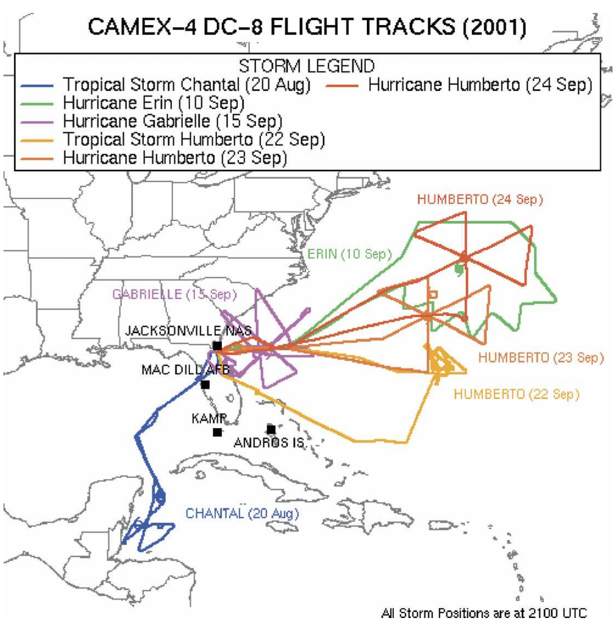

FIG. 5. Flight tracks of the NASA DC-8 over tropical cyclones flown during CAMEX-4.

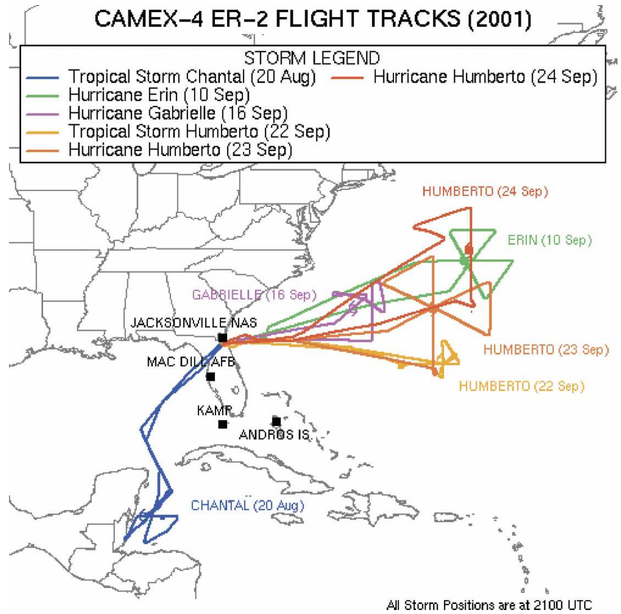

FIG. 6. Flight tracks of the NASA ER-2 over tropical cyclones flown during CAMEX-4.

Hurricane Erin was the second storm studied during CAMEX-4. It was planned as a mission to collect comprehensive observations by the NASA and NOAA aircraft over a 2-day period that could be used to either initialize or validate data assimilation studies by CAMEX Science Team members, NOAA scientists, or other members of the scientific community who conduct hurricane-modeling research. The data assimilation flights had an emphasis on mapping the inflow of moisture into the storm. The first flight investigating Hurricane Erin was on 10 September 2001. The DC-8 circumnavigated the storm (Fig. 7) in a sawtoothed pattern at approximately 3° out from the center launching 11 dropsondes along the midpoint of the legs and simultaneously collecting a significant volume of moisture profile data from the lidar Atmosphere Sensing Experiment instrument. Meanwhile, the NOAA P-3 and the ER-2 were focused on the inner core of the storm. The ER-2 flew over Erin and successfully launched eight dropsondes across the storm diameter, including the first to fall from the stratosphere into the eye of a hurricane. NOAA scientists on the P-3 detected two low-level circulation centers evident in the low-level cloud field. The second mission planned for Hurricane Erin had to be abruptly cancelled because of the tragic events of 11 September 2001. This storm was not sampled again.

Tropical Storm Gabrielle developed from a nontropical, low-level cutoff low that became increasingly well organized in the central Gulf of Mexico from 9 to 11

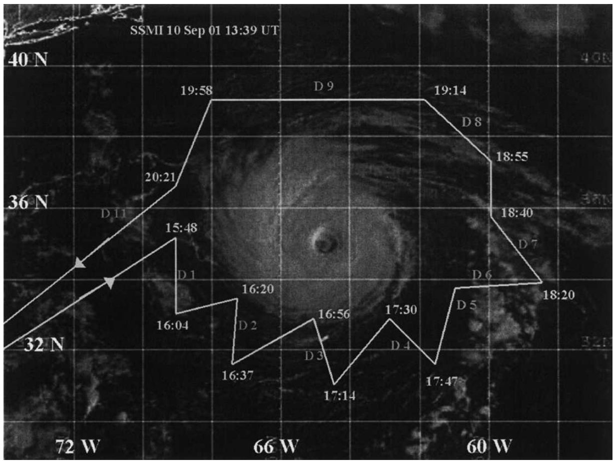

FIG. 7. The flight track of the NASA DC-8 around Hurricane Erin on 10 Sep 2001. Aircraft turn times are noted as are the locations of the eleven dropsonde releases depicted with D# notation. Image courtesy of R. Ferrare/NASA Langley Research Center.

September 2001. On 11 September, the storm was classified as a tropical depression, but was drifting eastward and continuing to gain strength. Two days later, on 13 September 2001, Gabrielle was 175 miles southwest of Venice, Florida, and had developed into a tropical storm. The next day, Gabrielle made landfall near Venice, Florida, and traveled northeastward across central Florida (Beven et al. 2003). Because of a combination of post–September 11 flight restrictions, high winds, and the proximity of the storm to NAS Jacksonville, both the ER-2 and DC-8 were not able to fly the storm until 15 September 2001. However the mobile KAMP ground validation instruments (Table 4), Shared Mobile Atmosphere Research and Teaching Radar (SMART-R) and the MIPS, did redeploy in the vicinity of Venice, Florida, and monitored Gabrielle at landfall. The MIPS team measured wind speeds of 32 m s^{-1} (62 kt) at landfall and the SMART-R radar estimated wind speeds at 40 m s^{-1} (78 kt) just offshore. Wind speeds diminished to 20 m s^{-1} (39 kt) as Gabrielle crossed central Florida. Once back out over the Atlantic Ocean, Gabrielle reintensified and moved northeast of Bermuda. On 15 September 2001, the DC-8 and a NOAA P-3 mapped the flow field around Tropical Storm Gabrielle during what was forecast to be an extratropical transition. The NOAA G-IV also flew a synoptic surveillance mission on 15 September 2001. A second mission was conducted on 16 September 2001 with the ER-2 and the P-3. This mission focused on documenting the unforecasted reintensification of the system by mapping the differences between the previous flight and this one.

The last of the four tropical cyclones studies during CAMEX-4 was Hurricane Humberto, which provided a significant opportunity for 3 days of consecutive sampling. On 22 September 2001, Humberto strengthen into a tropical storm. The CAMEX mission conducted on this day using the DC-8, ER-2, and one NOAA P-3 was a rainfall sampling mission that would be used to support quantitative precipitation estimation studies. The aircraft mapped the conditions near the developing storm center as well as the flow fields and thermodynamic fields in the surrounding environment. All three aircraft flew well-coordinated flight legs into the storm center at staggered altitudes. The most vigorous convection was found along the north side of the eye. The ER-2 mission was cut short 2 h earlier than the other aircraft in order to conserve flight hours and preserve the option of a coordinated mission on the next 2 days.

The Humberto missions conducted on 23 and 24 September 2001 included an unprecedented number of aircraft monitoring the storm's conditions. Four research aircraft including the DC-8, ER-2, and two NOAA P-3s flew into the interior of the storm on each of these days along with the operational Air Force Reserve 53rd Weather Reconnaissance Squadron WC-130 aircraft on 23 September 2001. Other operational aircraft activities included environmental sampling outside of the storm by the NOAA G-IV on both days.

During this 2-day period, Hurricane Humberto experienced a cycle of both increasing and decreasing intensity change. At 2100 UTC on 23 September 2001, Humberto was a rapidly strengthening hurricane that achieved category 2 status 6 h later with 44 m s^{-1} (85 kt) winds (Beven et al. 2003). The coordinated flights of the research aircraft mapped the inner core and outer regions of the storm as well as the near and far environment. Extensive cirrus outflow existed in all quadrants of the storm as well as a larger semicircular band of vigorous convection on the north side. The DC-8 encountered some moderate turbulence in the northern eyewall and a strong event at about 2205 UTC in the northwest eyewall. The storm was apparently near maximum intensity on this day. However, less than a day later on 24 September 2001, westerly shear caused the hurricane to lose strength. It was reclassified as a weakening category 1 storm. On this day, the aircraft flew a tightly coordinated pattern to focus on the vortex evolution and structure of the inner core.

Overall, six total aircraft monitored Hurricane Humberto on 23 September 2001. Five total aircraft were utilized on 24 September 2001. In addition to the remote sensing and in situ instrumentation many of the aircraft carried, all of the aircraft released dropsondes during the missions. A total of 100 dropsondes were released on each day of this 2-day period. In fact, the ER-2 performed the first-ever stratospheric release of a dropsonde to penetrate a tropical cyclone eye. The full breadth of the three-dimensional mapping conducted by the aircraft represents an unparalleled body of information covering a horizontal diameter across the storm center of nearly 2000 km and a vertical profile from below the ocean surface to 20 km above. These data will be especially useful for studies of hurricane intensity change studies and hurricane predictive model studies require initialization or validation information.

4. Data access and archive

The CAMEX data archive is available from the Global Hydrology Resource Center located at the National Space Science and Technology Center in Huntsville, Alabama. The National Space Science and Technology Center is a partnership formed under a cooperative agreement between the NASA Marshall Space Flight Center and the seven state research universities of Alabama. All NASA-funded CAMEX instrument data are either online or on near-line archive storage available for ready and easy access. The CAMEX Web site (http://camex.msfc.nasa.gov) provides a brief overview of the experiments, lists of participants, instruments, aircraft, documentation, a science presentation library, and most importantly a search-and-order capability for the datasets and science reports. Additional NOAA P-3 datasets associated with the coordinated research flights are available from NOAA AOML Web site (http://www.aoml.noaa.gov/hrd).

As described previously, the CAMEX aircraft were outfitted with instruments that sampled a wide range of atmospheric parameters from cloud microphysics to Doppler radar reflectivity, and from atmospheric electric fields to water vapor profiles. The individual instrument teams processed their respective instrument datasets. Each instrument team was responsible for collecting, processing, formatting, and performing quality assurance for their data. A description of each instrument dataset is included with the data files. In addition to the science instruments provided by the CAMEX principal investigators, the NASA ER-2 and DC-8 aircraft each carried an information collection and transmission system providing navigation, aircraft conditions, and environmental data measured by facility sensors. These data are stored in the CAMEX data archive and available for public distribution.

As part of the mission planning and daily field experiment summary process, the individual science teams and aircrew entered daily instrument reports, flight sortie reports, and mission scientist descriptions. These reports, along with the weather forecasts and weather summaries, provide a general overview of each day's events and mission objectives. This documentation and data are available from the both the CAMEX and HRD Web sites.

5. Summary

NASA sponsored two separate field campaigns in partnership with NOAA HRD and the USWRP during 1998 and 2001. These campaigns sampled a total of eight tropical storms and hurricanes: Bonnie, Danielle, Earl, and Georges during 1998 and Chantal, Erin, Gabrielle, and Humberto during 2001. These storms offered opportunities to monitor convective bursts, intensity change, asymmetric hurricane storm structures, precipitation processes, and landfalling impacts, just to name a few topics of interest. Information collected during these campaigns have been archived are readily available for distribution at the CAMEX Web site.

Analysis of this information has begun to successfully address the CAMEX research topics, and research results are being published. As an example, Heymsfield et al. (2001) have thoroughly examined the eyewall structure of Hurricane Bonnie and suggest that convectively induced downdrafts may contribute as much as 3 K to a hurricane's warm core. Whiteman et al. (2001) discuss the changing water vapor and cirrus cloud conditions, deduced from Raman lidar measurements, as Hurricane Bonnie passed east of Andros Island, Bahamas. Geerts et al. (2000) describe the intense convection that developed within the eye of Hurricane Georges due to orographic lifting during landfall in the Dominican Republic. Skofronick-Jackson et al. (2003) demonstrate how to estimate vertical content and particle size distribution of hurricane hydrometeors using CAMEX active and passive microwave airborne observations with an iterative retrieval algorithm, while Durden et al. (2003b) present a wind-dependent surface reference technique for airborne Doppler radar observations of hurricanes. Kamineni et al. (2003) discuss how high-resolution water vapor cross-sectional data contribute to improved hurricane intensity and track forecasts in a numerical model run in research mode on a few test cases, while Heymsfield et al. (2000) and Durden et al. (2003a) used CAMEX airborne radar observations to evaluate TRMM precipitation radar products.

This special issue includes contributions from both NASA and NOAA partners. These results pertain to topics addressing observations, parameterizations, and simulations of hurricane hydrometeors, warm cores, potential vorticity fields, vertically sheared wind fields, and storm evolution.

In July 2005, NASA implemented the next phase of tropical cyclone field studies. The Tropical Cloud System and Processes (TCSP) field program focused on the origins and life cycle of tropical cyclones. The TCSP field experiment was based in San Jose, Costa Rica, and was conducted in partnership with the NOAA HRD Intensity Forecasting Experiment. The NASA observations were collected from satellite, the instrumented NASA ER-2, Aerosonde, and radiosonde platforms. Data collection included observations of Gulf of Mexico hurricanes Dennis and Emily as well as Tropical Storm Gert.

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