NASA'S TROPICAL CLOUD SYSTEMS AND PROCESSES EXPERIMENT

Investigating Tropical Cyclogenesis and Hurricane Intensity Change

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High altitude research flights during the active 2005 Atlantic and eastern Pacific hurricane season yielded interesting and surprising observations, both within and above the clouds.

BACKGROUND AND MOTIVATION FOR TCSP. A key mandate of the National Aeronautics and Space Administration's (NASA's) Weather Focus Area is to investigate high-impact weather events, such as tropical cyclones, through a combination of new and improved space-based observations, high-altitude research aircraft, and sophisticated numerical models to improve the understanding and predictability of weather, climate, and natural hazards. One of the areas of tropical meteorology that remains elusive to both understanding and prediction is the genesis and intensification of tropical cyclones. The processes by which tropical disturbances develop into depressions, storms, or hurricanes (termed tropical cyclogenesis) remain one of the outstanding and fascinating research topics in meteorology. The

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tropical atmosphere is filled with disturbances of different scales throughout the storm season, but only a small percentage of them eventually become named tropical storms. For instance, only about 10% of the 60–70 tropical waves crossing the Atlantic in a given season become named tropical storms (Simpson et al. 1968). Forecasting the intensity change of storms that are already intense is of obvious practical importance, but so is anticipating the weak disturbances that will only remain rainstorms, and those that bear close watching for rapid intensification.

Large-scale influences on tropical cyclogenesis have been studied for many years, in part because such influences are measurable within the existing observational network. There is general agreement that tropical cyclones form in the Tropics or subtropics, usually over warm (>26°C) water with a sufficiently great depth, and only far enough from the equator where background rotation is present. Tropical cyclones also develop only when vertical wind shear over the depth of the troposphere is less than 10–15 m s^{-1} (e.g., Gray 1968; Kaplan and DeMaria 2003). Finally, tropical cyclones develop within regions of preexisting cyclonic relative vorticity in the lower troposphere (e.g., easterly waves, the monsoon trough, or the active part of the Madden–Julian oscillation).

The above concepts become much more difficult to apply when one considers the mesoscale evolution of developing tropical cyclones. Some tropical storms originate from mesoscale convective system (MCS) precursors within the preexisting regions of cyclonic vorticity noted above (Cotton and Anthes 1989; Gray 1998). Although MCSs occur frequently over the tropical oceans, only a few develop into tropical cyclones, and the mechanisms that either inhibit or favor development are still poorly understood. Over the last decade and a half, the focus on genesis became a search for the mechanism responsible for low-level vorticity sufficiently intense to initiate the wind-induced surface heat exchange (WISHE) process of Emanuel (1987). Several studies have proposed mechanisms for the generation of low-level vorticity by some form of vorticity transport or projection downward from the midlevels. These are the "top-down" theories of Bister and Emanuel (1997), Ritchie and Holland (1997), and Simpson et al. (1997). Bister and Emanuel (1997) proposed that a mesoscale region of light rainfall would act to humidify the low-level air, which contributes to increased production of low-level potential vorticity due to the favorable diabatic conditions. The key element in this hypothesis is the requirement of a precipitating region that cools and moistens the lower troposphere to the point at which the effects of cold downdrafts no longer inhibit the development of cyclonic winds at the surface. The latter two papers proposed a vortex merger theory in which successive mergers of midlevel mesoscale vortices (associated with MCSs) intensified the midlevel vortex. The midlevel merger process increases the horizontal and vertical scale of the vortex. They proposed that genesis would begin when the vertical scale had increased sufficiently to reach the surface.

In contrast to the top-down hypotheses mentioned above, "bottom-up" hypotheses generally describe the genesis process as being driven by low-level convergence that increases cyclonic vorticity near the surface through vortex stretching. Zhang and Bao (1996) find that a midlevel mesoscale convective vortex (MCV) provides the quasi-balanced forcing for the initiation and organization of deep convection, and that it is deep convection that contributes to the amplification of the low-level cyclonic vorticity through stretching. A similar hypothesis was advanced by Rogers and Fritsch (2001) and Chen and Frank (1993), who emphasized the role of the midlevel vortex and high midlevel humidity. These factors act to reduce the Rossby radius of deformation such that latent heat released from repeated convective bursts is retained locally. Furthermore, stretching associated with the repeated convective activity contributes to increased low-level vorticity. This mechanism was later confirmed by the cloud-resolving studies of Hendricks et al. (2004) and Montgomery et al. (2006). In their high-resolution numerical simulations, Montgomery et al. (2006) blend moist thermodynamic and dynamic processes in high-resolution numerical simulations to examine the development of a weak low-level cyclonic circulation prior to the ignition of the WISHE (heat engine) mechanism. They find that deep convective towers possessing intense cyclonic vorticity in their cores are the dominant coherent structures of a predepression disturbance. These vortical hot towers (VHTs) sustain themselves by consuming available potential energy in their local environment and by merging with neighboring towers. The population of VHTs statistically mimics a quasi-steady heating rate in the core of the mesoscale vortex and generates a system-scale transverse circulation with low-level inflow and upper-level outflow. The low-level inflow concentrates the preexisting and VHT-generated absolute angular momentum to the necessary amplitude threshold to start the hurricane heat engine.

Neither the top-down nor bottom-up theories have provided a full description of the role of vertical wind shear. It has been argued that in some cases moderate values of shear, which have a negative impact on mature hurricanes, might aid the early development of storms (Davis and Bosart 2003; Molinari et al. 2004). The process in general is as follows: vertical wind shear excites convection downshear of the developing storm, which creates middle- or low-level vorticity downshear. If sufficiently strong, the downshear vorticity can either become a new center and absorb the old (Molinari et al. 2004, 2006), or it can be absorbed by the old (Enagonio and Montgomery 2001). Either way, the storm can intensify by this process, possibly more than it would have in the absence of vertical shear (Reasor and Montgomery 2001).

Of course, the hypotheses above are not mutually exclusive. They suggest that tropical cyclones can form from one or multiple midlevel MCVs or convective bursts that themselves may contain an ensemble of VHTs. For these vortices to amplify the surface circulation, the core of the system likely must have sufficiently high relative humidity so that downdrafts do not inhibit development. This high humidity may often result from mesoscale precipitation regions that are associated with MCVs. Steranka et al. (1986), Rodgers et al. (1994), and Hennon (2006) find evidence from satellite data that, in many tropical cyclones, sustained convective bursts precede rapid intensification. The explicit processes by which an MCS with embedded MCVs, VHTs, and vertical wind shear develops into a tropical cyclone remains an unsolved problem.

SCIENTIFIC OBJECTIVES. To address many of the issues related to tropical cyclone formation and intensification, NASA conducted a field campaign in July 2005 known as the Tropical Cloud Systems and Processes (TCSP) experiment. TCSP research broadly addresses the following overarching scientific themes: 1) tropical cyclogenesis, structure, intensity change, moisture fields, and rainfall distribution; 2) satellite and aircraft remote sensor data assimilation and validation studies pertaining to tropical cyclone development; and 3) the role of upper-tropospheric/lower-stratospheric processes governing tropical cyclone outflow, the response of wave disturbances to deep convection, and the evolution of the upper-level warm anomaly. The following are some key questions related to tropical cyclone genesis and intensity change that are being examined:

- What processes govern tropical cyclogenesis in the eastern North Pacific and Caribbean: intensification of easterly waves into depressions, mesoscale generation of cyclonic vorticity, or some combination of both?
- What dynamical and thermodynamic processes involving both the atmosphere and upper ocean contribute to rapid intensification of tropical cyclones? This includes the frequent occurrence of convective bursts during the development stage and the role of vertical wind shear.
- How does the low-level vortex of a tropical cyclone become established? Processes to be investigated include the descent of midlevel mesoscale vortices, the generation of convective-scale VHTs, and the horizontal merger of vortices.

Additionally, during periods of inactive tropical cyclone development, TCSP research was focused on obtaining detailed observations of organized deep convective systems in various geographical settings, and flying calibration-validation underpasses of NASA satellites as orbits of opportunity arose. The TCSP science team, which includes the diverse group of government and academic scientists listed in Table 1, collected data on the multiscale (i.e., microphysical scale to synoptic scale) interactions of thermodynamic and dynamical processes governing the early evolution of tropical cyclones. TCSP science embodies a synergistic blend of observations and simulations, the so-called three-pronged approach, which includes aircraft measurements, satellite measurements, such as the Tropical Rainfall Measuring Mission (TRMM), and high-resolution numerical models, such as the Weather Research and Forecasting (WRF) model.

TCSP leverages a series of NASA field programs investigating tropical cyclones, beginning with the Third Convection and Moisture Experiment (CAMEX-3) in 1998, and continuing with CAMEX-4 in 2001 (Kakar et al. 2006). The TCSP campaign, and the earlier CAMEX programs, are vital components of the three-pronged approach. The strategy enables scientists to better understand the physics of tropical cyclones, improve model parameterizations and methods to assimilate diverse datasets, and provides a test bed for new observing technologies, such as Unmanned Aerial Vehicles (UAVs), onboard processing of information, and high-altitude dropwindsondes.

RESOURCES AND STRATEGIES IN THE FIELD. During the typical hurricane season, the Atlantic basin is generally quiet during the month of July. TCSP was formulated with the assumption that the most concentrated region of tropical storm

Table 1. TCSP Science Team members.

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Richard Blakeslee	NASA Marshall Space Flight Center
Mark Bourassa	The Florida State University
Scott Braun	NASA Goddard Space Flight Center
Daniel Cecil	University of Alabama Huntsville
William Frank	The Pennsylvania State University
Paul Ginoux	NOAA/Geophysical Fluid Dynamics Laboratory
Michael Goodman	NASA Marshall Space Flight Center
Jeffrey Halverson	University of Maryland, Baltimore County
Gerald Heymsfield	NASA Goddard Space Flight Center
Robbie Hood	NASA Marshall Space Flight Center
Tiruvalam Krishnamurti	The Florida State University
Bjorn Lambrigtsen	Jet Propulsion Laboratory, California Institute of Technology
Guosheng Liu	The Florida State University
Michael Mahoney	Jet Propulsion Laboratory, California Institute of Technology
Greg McFarquhar	University of Illinois at Urbana–Champaign
Robert Meneghini	NASA Goddard Space Flight Center
John Molinari	University at Albany, State University of New York
Robert Rogers	NOAA/Atlantic Oceanographic and Meteorological Laboratory
Karen Rosenlof	NOAA/Aeronomy Laboratory
Wayne Schubert	Colorado State University
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Chris Snyder	National Center for Atmospheric Research
Francis Turk	Naval Research Laboratory
Christopher Velden	University of Wisconsin—Madison
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Edward Zipser	University of Utah

activity in the world is *climatologically* in the eastern North Pacific (EPAC) region during July (Elsberry et al. 1987). This motivated our decision to conduct the mission out of San Jose, Costa Rica. Such a location allows for ready access to storms undergoing genesis along the west coast of Central America and Mexico, while also allowing for targets of opportunity in the Caribbean or the Gulf of Mexico.

Twelve separate missions totaling approximately 85 flight hours were flown by the NASA ER-2 high-altitude (~20 km) research aircraft, carrying a payload of in situ and remote sensing instrumentation. Table 2 presents a synopsis of these missions. The ER-2 served as the primary platform for collecting a variety of remotely sensed data on the genesis, intensification, and decay of several Atlantic and EPAC tropical disturbances. Sorties were flown above Tropical Storm Gert, the precursor to Tropical Storm Eugene, and Hurricanes Dennis and Emily. Detailed information about the TCSP campaign, daily mission summaries, satellite animation, flight tracks, and quick-look images of the data can be found by visiting the TCSP Web site (online at http://tcsp.nsstc.nasa.gov).

Many of these missions were flown in coordination with the National Oceanic and Atmospheric Administration/Aircraft Operations Center (NOAA/AOC) WP-3D, Orion, research aircraft led by NOAA/Atlantic Oceanographic and Meteorological Laboratory (AOML) Hurricane Research Division (HRD) scientists as part of HRD's 2005 Intensity Forecast Experiment (IFEX; see Rogers et al. 2006). The advantages of such a collaboration are twofold: 1) the NASA ER-2 flies high (over the storms) and the NOAA WP-3D flies low (around and through the storms), ensuring near-complete vertical coverage of the tropical cyclone via remote sensing, in situ, and expendable instruments from 21 km in the atmosphere downward through the planetary boundary layer and oceanic mixed layer; and 2) the experience, knowledge, and capabilities of each agency are combined to effectively address unresolved critical issues surrounding the genesis of tropical cyclones and their rapid intensification. For instance, during TCSP the NASA ER-2 and NOAA WP-3D were able to fly a total of five back-to-back missions for continuous coverage within the pregenesis phases of Tropical Storm Eugene. Five consecutive multiaircraft missions also captured the complete life cycle of a tropical cyclone (Gert) from its genesis off the Yucatan Peninsula to landfall and dissipation over the mountains of Mexico.

Figure 1 shows the instrumentation that was carried on board the ER-2. The types of instruments are similar to those from NASA satellites, measuring clouds [the Cloud Radar System (CRS) and the Moderate Resolution Imaging Spectroradiometer (MODIS) Airborne Simulator (MAS)], precipitation [the ER-2 Doppler Radar (EDOP) and Advanced Microwave Precipitation Radiometer (AMPR)], electric charge and lightning [lightning instrument package (LIP)], and thermodynamic profiles [microwave temperature profile (MTP) and high-altitude MMIC Sounding Radiometer (HAMSR)]. Unlike any satellite, the resolution is much greater and the ER-2 flight track can be optimized for each target. In addition to the ER-2, NASA operated Aerosonde unmanned aerial vehicles (UAVs) on eight missions to sample the eastern North Pacific boundary layer (wind and thermodynamics) during both pregenesis and inactive phases of TCSP. NASA also deployed 6-hourly GPS radiosondes from Juan Santamaria International Airport in Costa Rica to support scientific and aircraft operations, including validation of NASA's *Aura* satellite.

Table 2. Synopsis of missions flown during TCSP involving both the ER-2 and NOAA P-3 research aircraft. (TD = tropical depression, TS = tropical storm.)

Date	Aircraft	Mission description
2 Jul	ER-2 (1 flight)	MCS–deep convection—Caribbean
5–9 Jul	ER-2 (3 flights); P-3 (2 flights)	Dennis TD-to-TS-to-category 1, category 3
14–16 Jul	ER-2 (2 flights); P-3 (5 flights)	Eastern North Pacific pregenesis
17 Jul	ER-2 (1 flight)	Emily category 4
20 Jul	ER-2 (1 flight)	MCS–deep convection—Nicaragua
23–25 Jul	ER-2 (3 flights); P-3 (4 flights)	Gert wave-to-TD-to-TS-to-landfall
27 Jul	ER-2 (1 flight)	MCS–deep convection—Panama

Collaboration with Costa Rican scientists, students, and officials from the Ministry of Science and Technology were essential to the success of the TCSP campaign. Scientists from the University of Costa Rica (UCR) and local forecasters provided valuable insight into regional cloud and rainfall patterns influenced by the complex terrain. The frequent occurrence of nocturnal fog and low visibility in upslope flow conditions within the valley of San Jose proved very challenging for ER-2 operations into and out of the airfield.

The TCSP field campaign benefited from a wealth of available real-time satellite imagery and products, particularly the special tasking of the NOAA *Geostationary Operational Environmental Satellite (GOES)-11* satellite in rapid scan mode over Central America. Data from the Costa Rican regional lightning detection network were routinely overlaid on the satellite imagery to help identify the most vigorous convective cores. TCSP mission scientists could monitor the real-time progress of the ER-2 aircraft by noting its current position and track in relation to these high-resolution cloud and lightning features.

Telemetry of the ER-2 information (location and electric fields) was facilitated by the Research Environment for Vehicle-Embedded Analysis on Linux (REVEAL) system developed at the NASA Dryden Flight Research Center. The REVEAL system, which is a flexible sensor acquisition and processing system, provided the TCSP science team with over-the-horizon mission monitoring capabilities throughout the flight. Satellite imagery and products were also

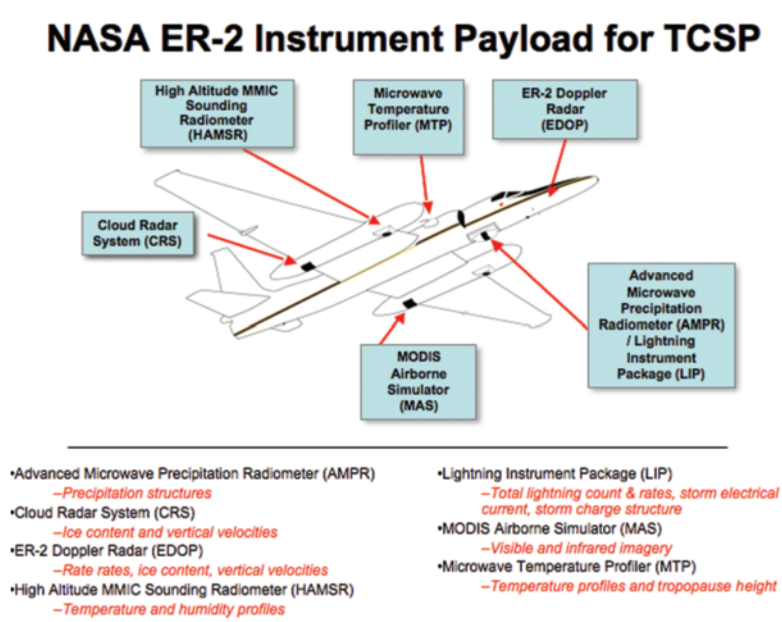

Fig. 1. Scientific instrumentation flown on board the NASA ER-2 aircraft during TCSP.

made available through sites located at the University of Wisconsin—Madison–Cooperative Institute for Meteorological Satellite Studies (UW–CIMSS), and the Naval Research Laboratory (NRL) at Monterey, California. [The Web sites can be found online at www.nrlmry.navy.mil/tc_pages/tc_home.html (select year 2005 and view EPAC systems with TCSP in the storm name), and UW–CIMSS http://cimss.ssec.wisc.edu/tropic/tcsp.] All of the satellite data collected in real time are available for postanalysis on these two sites or the TCSP Web site. Examples of derived products of special interest to the TCSP campaign include high-density cloud motion winds derived at CIMSS on an hourly basis from the *GOES-11* 5-min rapid scan imagery. (An example of this product can be found online at the UW–CIMSS Web site: http://cimss.ssec.wisc.edu/tropic/tcsp/archive/winds/18Jul2005-12z-upperwindsS.gif.) The TCSP field campaign will in turn offer opportunities for satellite data validation and numerical model forecast impact experiments. Several investigators plan satellite data assimilation as part of a modeling component of the project.

MAJOR ACCOMPLISHMENTS. Figure 2 illustrates a satellite mosaic of the principal storm systems into which TCSP aircraft flew, along with the track and intensity of each storm. During the 2005 hurricane season, the Caribbean was particularly active instead of the eastern North Pacific, with two of the strongest July hurricanes on record occurring in the Caribbean. There were seven Atlantic tropical storms before 1 August compared to the previous record of five in 1997. Two of these storms (Hurricane Dennis and Hurricane Emily) were category 4 or greater and are the strongest July storms in the Atlantic basin on record.

The first priority of TCSP was to investigate the development of tropical cyclones from locally generated and/or traveling wave disturbances. Fortunately, there were several targets of opportunity in the Caribbean and eastern North Pacific. The evolution of Dennis was well sampled by ER-2 and WP-3D aircraft from the tropical depression stage through maturity. Seven ER-2 and WP-3D aircraft missions were flown into a region of the eastern North Pacific where cyclogenesis was predicted to occur; one of

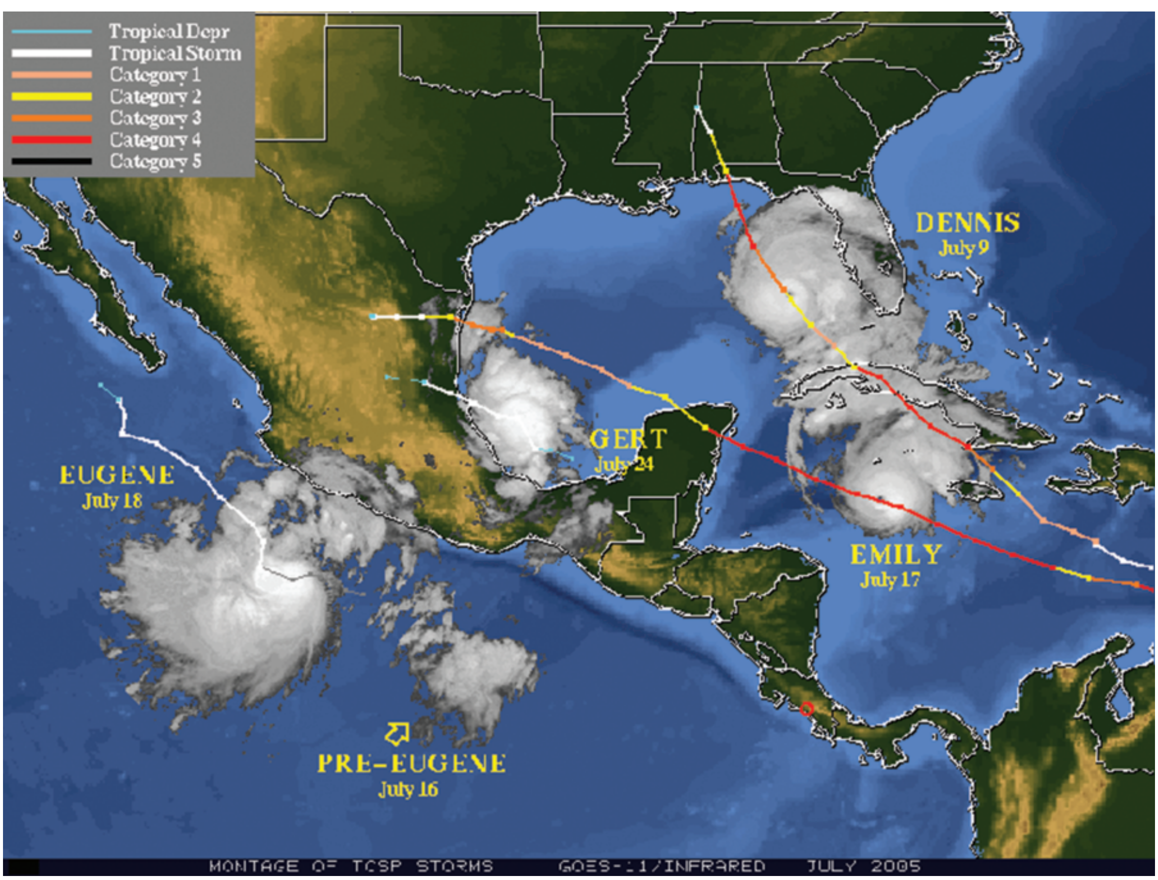

Fig. 2. Satellite mosaic showing the principal storms investigated by NASA and NOAA aircraft during TCSP. The track and intensity for each storm are also shown.

these flights captured the pregenesis phase of Tropical Storm Eugene. Finally, late in July the NASA and NOAA aircraft sampled the complete life cycle of Tropical Storm Gert, successfully capturing the transition of an easterly wave encroaching on the Yucatan Peninsula into a depression, tropical storm stage, and subsequent landfall near Tampico, Mexico.

Hurricane Dennis. During the first week of TCSP, Tropical Storm Dennis formed in the southeast Caribbean. Three coordinated flights between the NOAA P-3s and the ER-2 were performed on 5, 6, and 9 July. These flights covered the evolution of Dennis from a tropical depression to a tropical storm, and later to a hurricane. During the mission, the National Hurricane Center upgraded Tropical Storm Dennis to a category-1 hurricane.

Based on the missions into Hurricane Dennis, TCSP scientists will address issues related to the second TCSP science question posed in section 2—the role of convective bursts during tropical cyclone development and intensification using both satellite and aircraft information. During the second coordinated flight on 6 July, the NASA ER-2 and NOAA P-3 flew missions to investigate the development and intensification of Tropical Storm Dennis in the southeast Caribbean off the north coast of Venezuela. Figure 3 displays passive microwave imagery at three different times capturing the development of Dennis on 6 July and an overlay of the ER-2 flight track on a TRMM 85-GHz image. The mission was flown during the burst's long life cycle, as deep convection organized into a partial eyewall. In Fig. 4, the vertical precipitation structure of the burst observed by the

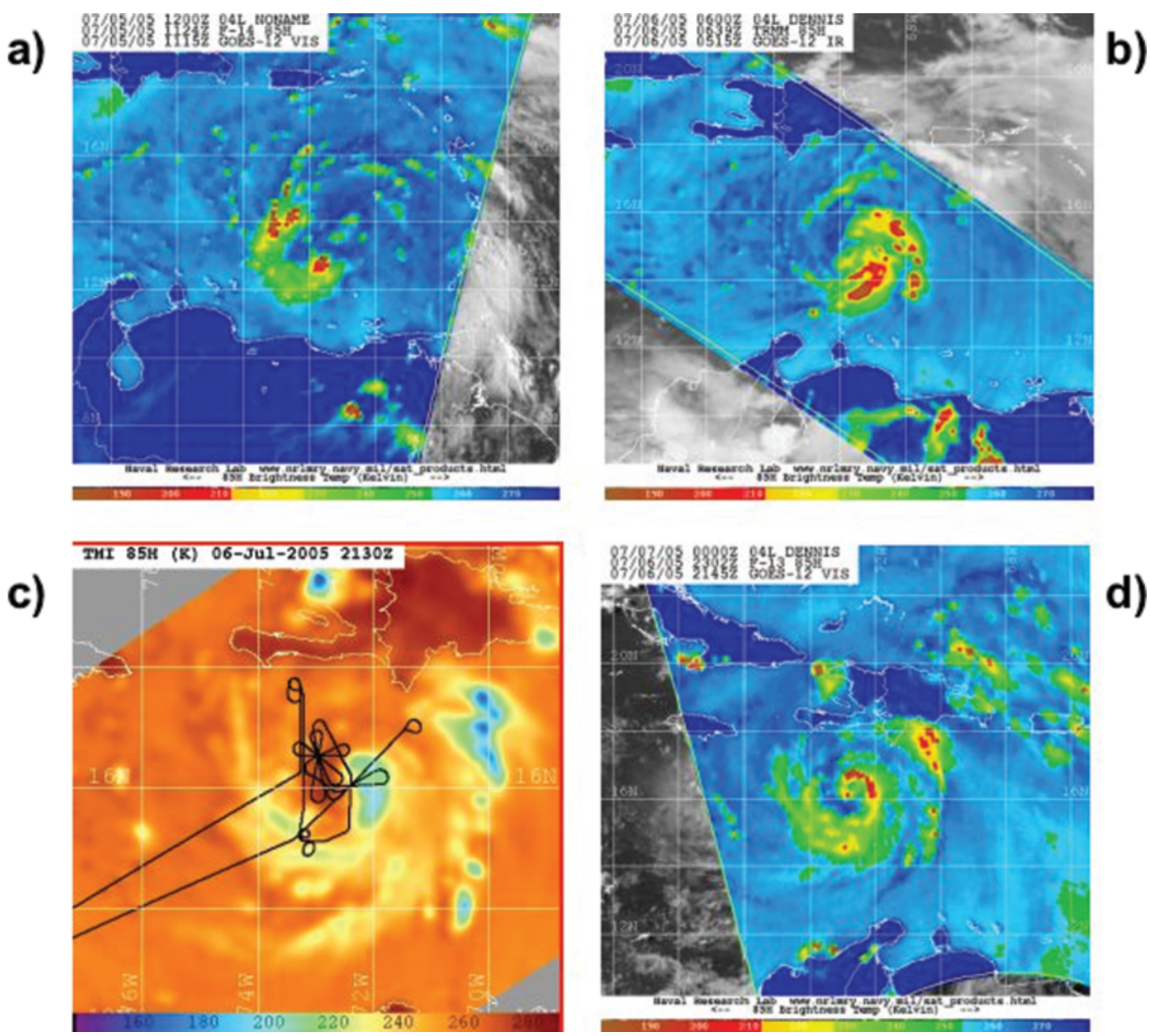

Fig. 3. Passive microwave imagery from the DMSP and TRMM satellites showing the evolution of precipitation features in the 86-GHz channel for Hurricane Dennis at (a) 1124 UTC 5 Jul, (b) 0639 UTC 6 Jul, (c) 2130 UTC 6 Jul, and (d) 2302 UTC 6 Jul 2005. The ER-2 flight track is overlaid on (c).

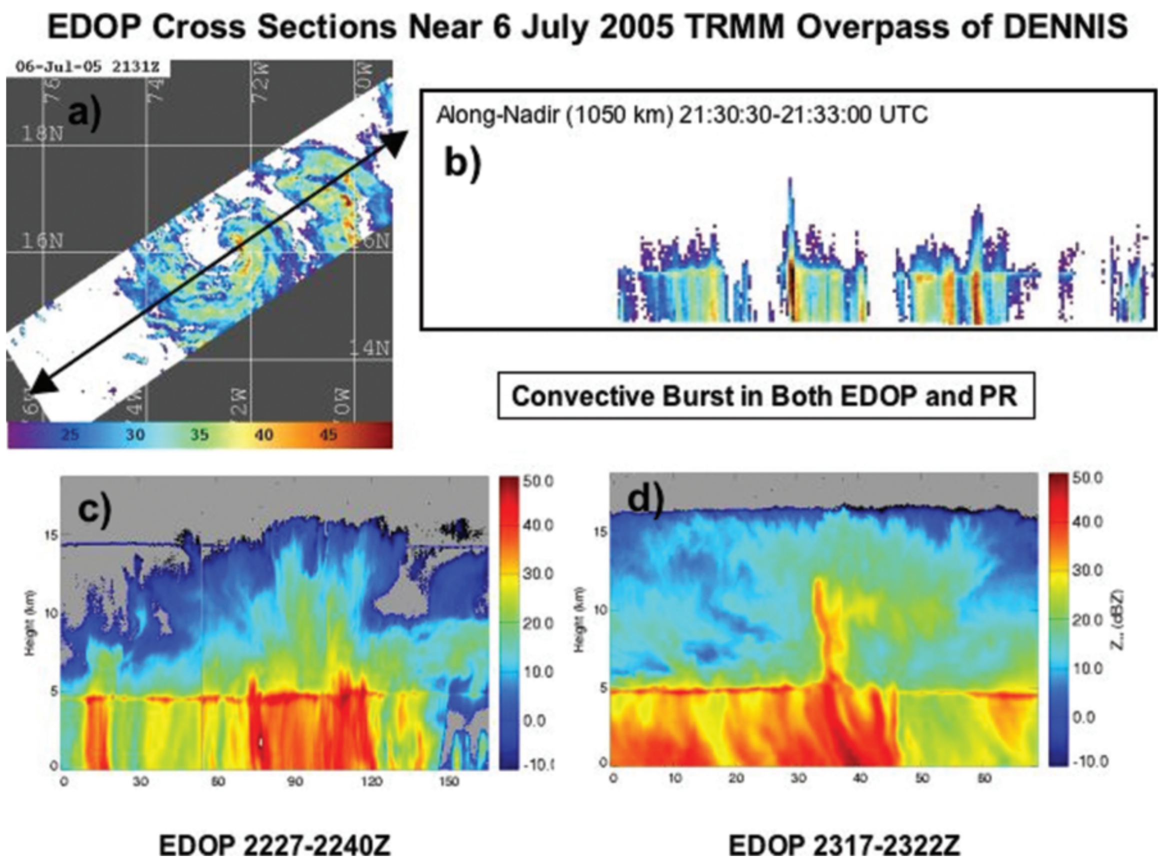

Fig. 4. (a) TRMM overflight of Hurricane Dennis showing Precipitation Radar reflectivity (dB*Z*) at 2131 UTC 6 Jul, (b) along-track cross section of TRMM vertical reflectivity structure at 2131 UTC 6 Jul [along orientation of black arrow in (a)], (c) and (d) EDOP cross sections of vertical reflectivity structure sampled between 2227–2240 and 2317–2322 UTC, respectively.

TRMM Precipitation Radar is compared with observations collected by EDOP (at much higher horizontal and vertical resolution) within 2 h and 10–20 km of the TRMM-observed precipitation cells.

The two aircraft not only documented the meso–convective-scale interactions within Dennis, but also sampled microphysical processes in the storm's inner core and rainbands. Two passes through the eye of Hurricane Dennis (Fig. 5, top) were conducted by the NOAA P-3 during the flight on 6–7 July, each pass coordinated with the NASA ER-2. Several minutes prior to each eyewall penetration, the P-3 climbed from the +5° to –3°C temperature levels, followed by descents that included sampling in the eyewall and eye (Fig. 5, middle). Each penetration of the eye was devoid of particles (Fig. 5, top). The eyewall penetrations, at temperatures above 0°C, sampled drops up to 5 mm (Fig. 5, bottom). This would indicate that the precipitation process was not efficiently removing all large drops, which were likely being lifted to subfreezing temperatures where they could presumably freeze to graupel. There was no isothermal layer during the climbs or descents, indicating that the region sampled by the P-3 was convective. Nonetheless, large aggregates, for the most part unrimed, were observed. This would suggest that the large-scale lifting in and around the eye was insufficient to produce much cloud water or drop formation. These penetrations would suggest that the cloud and rain water was restricted to the eyewall, and that snow aggregates were efficiently eliminating cloud water in the flanking regions. Analyses from data such as these will help us to understand the microphysical processes that are crucial for both modeling efforts and the satellite remote sensing of hurricanes.

Hurricane Emily. Another unexpected opportunity during TCSP was the development of category-5 Hurricane Emily in the same region where Dennis initially formed. The mission to study Emily occurred on 17 July when it was already a category-4 storm. As Emily moved toward the Yucatan Peninsula and the Texas–Mexico border, TCSP scientists decided to fly only the ER-2 for this mission since NOAA/HRD

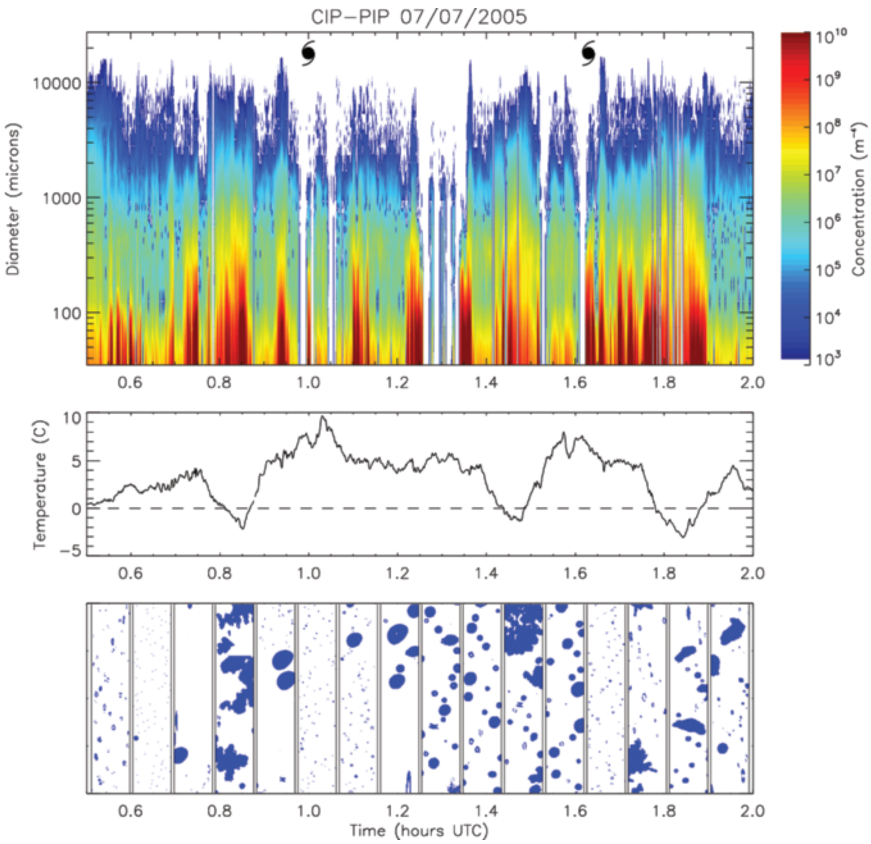

FIG. 5. (top) Particle size distribution measurements during two NOAA P-3 penetrations through the eye of Hurricane Dennis. The hurricane symbols show the locations of the eye. The color coding shows representations of the particle size distributions, with an average size distribution plotted over 5-s intervals along the time (abscissa) axis. Concentrations are color coded as a function of diameter (ordinate) according to the color chart shown. (middle) Temperature trace, with 0°C level shown with a dashed line. (bottom) Examples of images of particles from the 2D-C at locations across the penetrations. The distance between vertical bars is about 1 mm.

staff were anticipating the operational tasking of the WP-3D by the NOAA/National Hurricane Center/Tropical Prediction Center.

The focus of the Hurricane Emily flight was to document the convective structures of an intense hurricane with detailed measurements of the eyewall as the main objective and the sampling of intense convection in outer rainbands as the secondary objective. The ER-2 flew over Hurricane Emily in the early morning hours of 17 July as the storm passed between Honduras and the Cayman Islands. Prior to the ER-2 launch, the Air Force Reserve recorded a deepening from 953 hPa at 0541 UTC 16 July to 929 hPa at 2340 UTC. The last Air Force fixes of the night showed a rapid filling to 943 hPa by 0534 UTC 17 July.

During the very first eye crossing (east-southeast–west-northwest) by the ER-2, the pilot encountered strong turbulence (Figs. 6c,e). Data collected by the ER-2 EDOP and AMPR instruments during this flight (Figs. 6c,e) showed a compact eye about 30 km across, with the most impressive evidence thus far of intense convection in the eyewall of a hurricane. This convection extended up to nearly 17-km altitude with unusually high reflectivities at high altitudes (i.e., ~40 dB*Z* up to ~15 km). AMPR and HAMSR showed low brightness temperatures indicative of precipitation-sized ice. The AMPR Precipitation Index (API; Fig. 6c) merges information content from four frequencies of brightness temperatures into an indicator of precipitation ice and water. Note the purple shades of the API around the hurricane eye denoting ice scattering in three frequencies, suggesting large or graupel-sized ice particles. The LIP instrument detected very strong electrical activity during this pass (Figs. 6b,d). The maximum electric field is around 9 kV m^{-1}, one of the highest fields ever measured at the ER-2 altitude, (see Hood et al. 2006 for a discussion of the AMPR, LIP, and the API). The *GOES-11* brightness temperature (Fig. 6a) suggests a very intense isolated cell within Emily's eyewall. After two passes across the eye, the ER-2 pilot judged it unsafe to continue the planned pattern. This was the first time that hurricane convection had caused a safety concern for the ER-2 pilot at ~20-km altitude. A backup plan was quickly formulated, executing a box-type pattern just outside the eyewall. This allowed continued mapping of the inner core. A movie loop of the ER-2 aircraft track superimposed over *GOES-11* infrared images and lightning network data is available at the TCSP Web site.

Intense thunderstorms in the eyewalls of mature hurricanes are infrequent (Molinari et al. 1999; Cecil et al. 2002) and their role in hurricane dynamics is still uncertain. Recent research from the TRMM satellite suggests that extremely deep eyewall clouds are associated with a 70% likelihood of intensification (Kelley et al. 2004). Convective bursts tend to predominate in the premature stage of tropical cyclones (Hennon 2006), as was the case during the development of Dennis. The implications of very tall towers within the eyewall of such a strong storm as Emily, near its peak intensity, need to be better understood. While TRMM has sampled similar cases of intense thunderstorms in category-4 and -5 hurricanes, this is the first time that we have been able to obtain highly detailed, close-up measurements of such a storm from the ER-2.

Tropical Storm Eugene. On 14–16 July, TCSP forecasters and scientists examined numerical model guidance and analyses suggesting heightened potential for genesis in the EPAC. Back-to-back missions were flown by the NASA and NOAA aircraft, surveying MCSs within the intertropical convergence zone (ITCZ) west of Central America. Figure 7 illustrates the closely coupled flight tracks of the NOAA WP-3D and NASA ER-2 research aircraft on an infrared satellite view of the pre-Eugene convective environment, with upper-level (cloud derived) wind vectors superimposed. This region was characterized by persistent weak shear and upper-level diffluence. On numerous occasions, deep convection and associated midlevel vortices were identified through analysis of dropsondes, Doppler radar, and flight-level winds. Ongoing analyses of satellite data and manned (ER-2, WP-3D) and unmanned (Aerosonde) aircraft data—in combination with numerical modeling efforts—will reveal if one or more of these vortices and attendant convective systems served as the precursor to Tropical Storm Eugene. These studies will address whether or not vortex merger and amplification (the top-down vorticity hypothesis discussed in section 1) played a role in the eventual spinup of the tropical storm, which emerged on the northern edge of the pregenesis region (beyond the operating range of TCSP aircraft) within a day of the last survey flight.

Tropical Storm Gert. Five missions were flown into Tropical Storm Gert during its life cycle, commencing when the storm was just an open wave near the

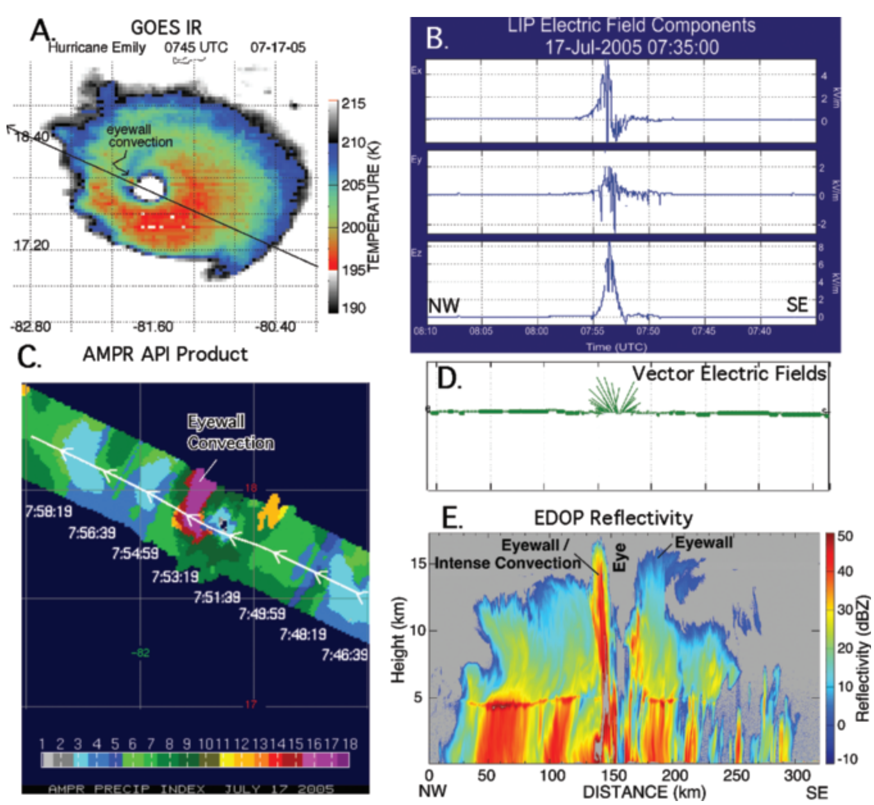

FIG. 6. Pass across the eyewall of Hurricane Emily on 17 Jul 2005. Shown are (a) the enhanced IR GOES image with the ER-2 flight track, (b) LIP component electric field products, (c) AMPR API product, (d) LIP vector electric field, and (e) EDOP reflectivity cross section. (b), (d), (e) The NW–SE time plots with time decreasing toward the right. For (b) the components of the electric field are in aircraft coordinates (Ex = nose to tail, Ey = wing to wing, and Ez = up to down). The various discontinuities in the fields are due to lightning flashes in the eyewall. For (c) darker shades of green indicate increasing rain rates with some precipitation ice aloft, while orange, red, and purple shades indicate increasingly large/abundant ice due to scattering in AMPR's lower-frequency channels. For (d) the horizontal line is the aircraft track at altitude (nominally, 20 km); green barbs are a representation of the vector electric field along the aircraft track. The length of the barbs is proportional to the magnitude of the electric field while the angle of the barb represents the direction of the electric field.

Yucatan Peninsula until landfall as a tropical storm. Early on 23 July (Fig. 8a), the NASA ER-2 and NOAA WP-3D flew coordinated missions in the vicinity of intense convection east of the Yucatan Peninsula and then sampled the structure of the easterly wave along the northern coast of the peninsula. A second WP-3D flight was conducted in the latter half of 23 July and surveyed the easterly wave as it moved west of the peninsula and transitioned into a depression (Fig. 8b). During this period, convection was weak and scattered in the region. Early on 24 July, intense convection redeveloped over the Bay of Campeche in association with the depression (Fig. 8c). Coordinated flights of the ER-2 and P-3 (Fig. 9) characterized the wind and precipitation structure of the depression as it strengthened into a tropical storm on 24 July. Portions of the mission focused on sampling the rapidly intensifying convection to determine the role of convective bursts in the genesis process. A solo P-3 flight continued to investigate Gert as the storm neared the coast of Mexico late on 24 July. This was followed by a solo ER-2 flight to investigate Gert's landfall on 25 July.

Among the questions that arise from the large-scale analyses and satellite data for this case are (i) the influence of Central American orography on the wave structure and convection—a numerical simulation shows northwesterly flow being funneled along the

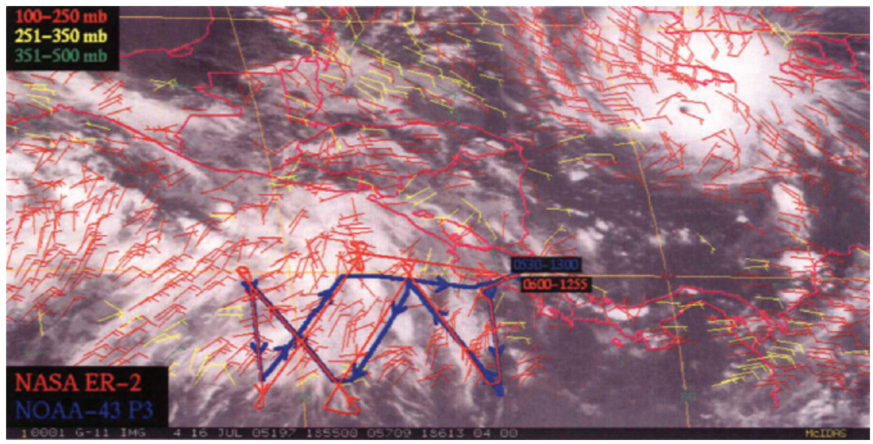

Fig. 7. Flight track of NASA ER-2 (red) and NOAA P-3 (blue) on a joint mission investigating the pregenesis of Tropical Storm Eugene on 16 Jul 2005 over the eastern North Pacific. Flight tracks are overlaid on the *GOES-11* infrared cloud-top temperature field with upper-level rapid scan wind vectors superimposed. Hurricane Emily (flown the next day) occupies the upper-right portion of the image.

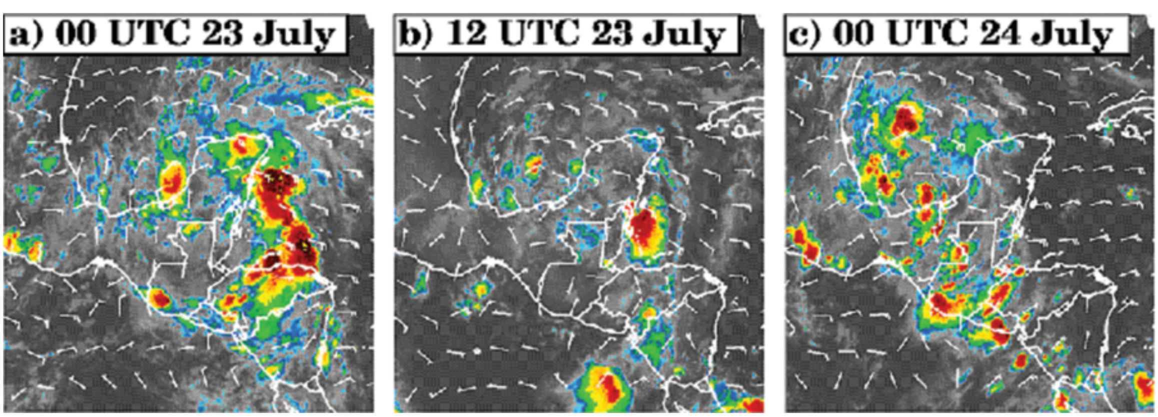

Fig. 8. The 1000-hPa winds from the NCEP global analyses show the broadscale wave clearly at (a) 0000 UTC 23 Jul as well as two primary regions of convection on each side of the Yucatan Peninsula. The only circulation center is found east of the peninsula. (b) By 1200 UTC 23 Jul, two distinct circulation centers are present. The eastern center has fallen well behind the wave axis and subsequently weakens. The second circulation center is near the wave axis in the far southern Gulf of Mexico and is also associated with active but not widespread convection. This is the region in which Gert formed. These two images show the complexity that arises as the wave crosses from water to land and back to water. (c) The final image at 0000 UTC 24 Jul shows that only one circulation center remains, in the southwestern Gulf, with significant convection occurring within it. Vorticity fields from the NCEP analyses confirm that the center is broad and, like the convection, not clearly focused. The 12 h before and after this time are most interesting for the diagnosis of how this storm forms within the easterly wave.

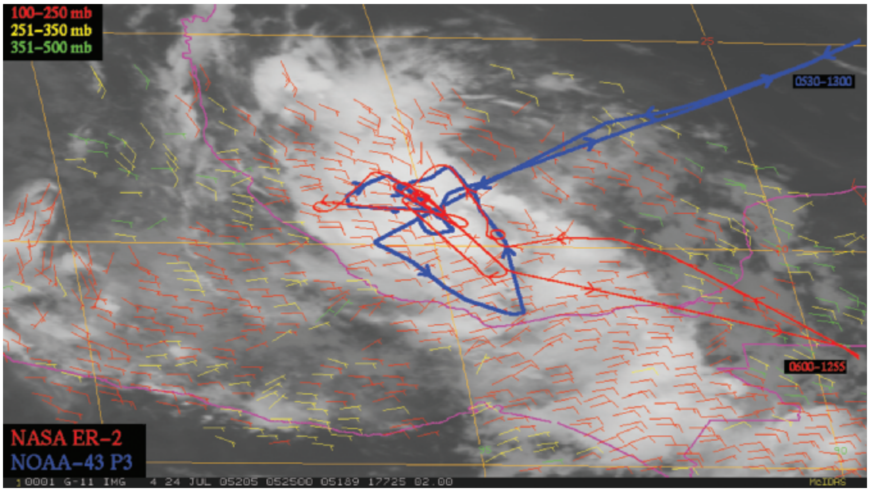

FIG. 9. Flight track of NASA ER-2 (red) and NOAA P-3 (blue) on a joint mission investigating the genesis of Tropical Storm Gert on 24 Jul 2005 west of the Yucatan Peninsula. Flight tracks are overlaid on the *GOES-11* infrared cloud-top temperature field with upper-level rapid scan wind vectors superimposed.

terrain, helping to amplify the circulation; (ii) the factors that determine where the depression and storm develop inside the wave—multiple circulation centers were found by aircraft and satellite, but not all were truly the focus of the cyclogenesis process; and (iii) the relative influences of multiple scales, from the synoptic down to the convective scale, on the location and timing of tropical cyclogenesis—the synoptic-scale wave had vigorous upper-level outflow and repeated mesoscale convective systems for days prior to cyclogenesis.

In order to address these questions, extensive analysis of all of the airborne observations must be conducted. However, because the airborne observations are limited in both space and time, these data must be complemented by information from other sources, including operational (GOES) and research [TRMM, *Aqua*, and the NASA Quick Scatterometer (QuikSCAT)] satellites as well as simulations from high-resolution numerical models such as WRF. The TRMM satellite passed almost directly over Gert during cyclogenesis, providing an excellent mapping of the rainfall rates (Fig. 10a) and vertical reflectivity profiles at this crucial time. A high-resolution simulation of Gert using the WRF model reproduces many aspects of the precipitation structure (Fig. 10b) of the storm when compared to the TRMM data and generates a strong low-level cyclonic circulation.

New remote sensing technology will also provide beneficial insight into Gert's genesis. Figure 11 displays complimentary EDOP and CRS observations of stratiform rain in developing Tropical Storm Gert.

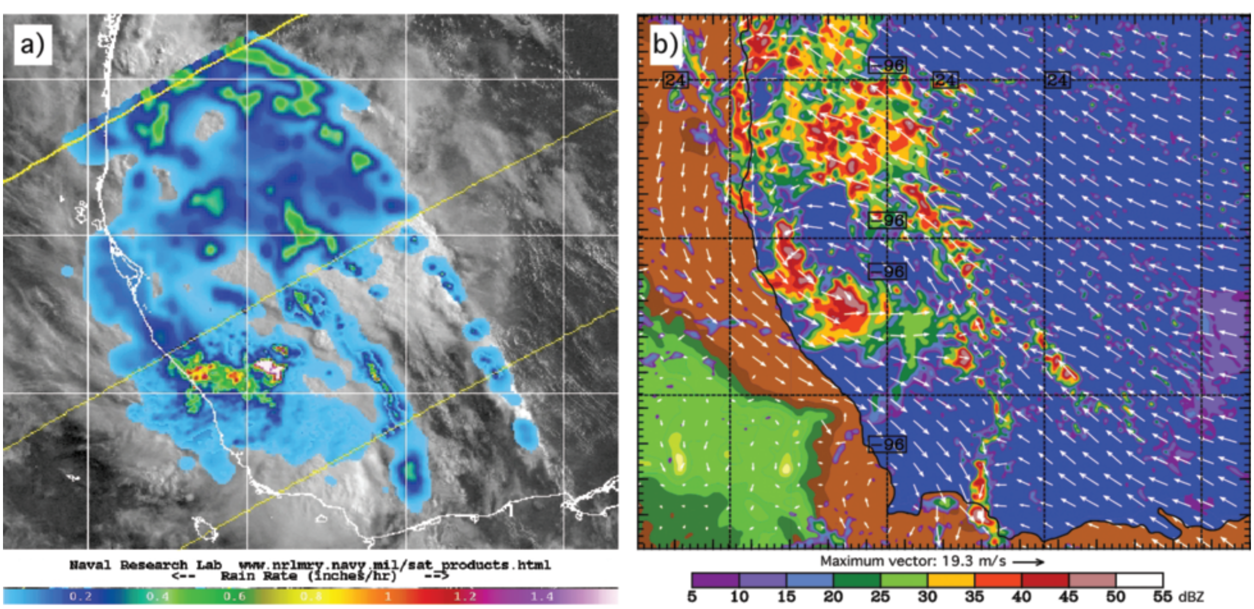

FIG. 10. A comparison of satellite remotely sensed rainfall and that from a numerical model simulation of Gert. (a) TRMM-derived rainfall rates at 1435 UTC 24 Jul and (b) simulated radar reflectivity and winds at 0.5 km at 1400 UTC from a 2-km grid-scale simulation using the WRF model.

The EDOP excels with finescale observations of vertical precipitation structure, brightband morphology, and the vertical motion field within convective updrafts and downdrafts. The CRS, which uses the same frequency (95 GHz) as the NASA CloudSAT (launched 2 June 2006), provides higher-resolution vertical profiles of weak reflectivity cloud features. Finescale, precision radiometric retrievals of the vertical temperature structure using the ER-2 Microwave Temperature Profiler (MTP) were made over the tropical cyclone and within its near environment. By converting the MTP temperature profiles measured during Gert's landfall on 25 July to constant potential temperature surfaces, or isentropes (Fig. 12), one can elucidate details of convectively generated gravity waves and other structure in the lower stratosphere. The pronounced, coherent dip in isentropes between 0500 and 0700 UTC along the flight track implies a region of mesoscale subsidence over the top of Gert's circulation (everywhere north of the red line) at 20-km altitude. These difficult-to-obtain high-altitude measurements are intriguing and suggest that the air column within the statically stable stratosphere can be dynamically active over tropical cyclones of even modest intensity.

SUMMARY AND PROMISING AREAS OF FUTURE RESEARCH. The NASA TCSP experiment was one of a comprehensive suite of campaigns investigating Atlantic tropical cyclones in 2005, which also include the NOAA/IFEX (Rogers et al. 2006) conducted during July–November and the National Science Foundation–sponsored Rainband and Intensity Change Experiment (RAINEX; Houze et al. 2006) missions during August–September. The four storms investigated during TCSP sampled a broad spectrum of tropical cyclone evolution in the Americas, ranging from the transition of an easterly wave into a depression, pregenesis embedded within the Pacific ITCZ, the mature stage of an unusually intense hurricane, and landfall/dissipation. The TCSP datasets, analyses, and numerical investigations promise to yield new insights into several vexing questions surrounding the investigation of tropical cyclone genesis. For instance, the Gert and Eugene missions will address the top-down versus bottom-up theories of vortex consolidation and amplification and the influence of shear on genesis. The three U.S. agency–sponsored field campaigns of 2005 also attest to the vigorous scientific interest surrounding the behavior of severe tropical

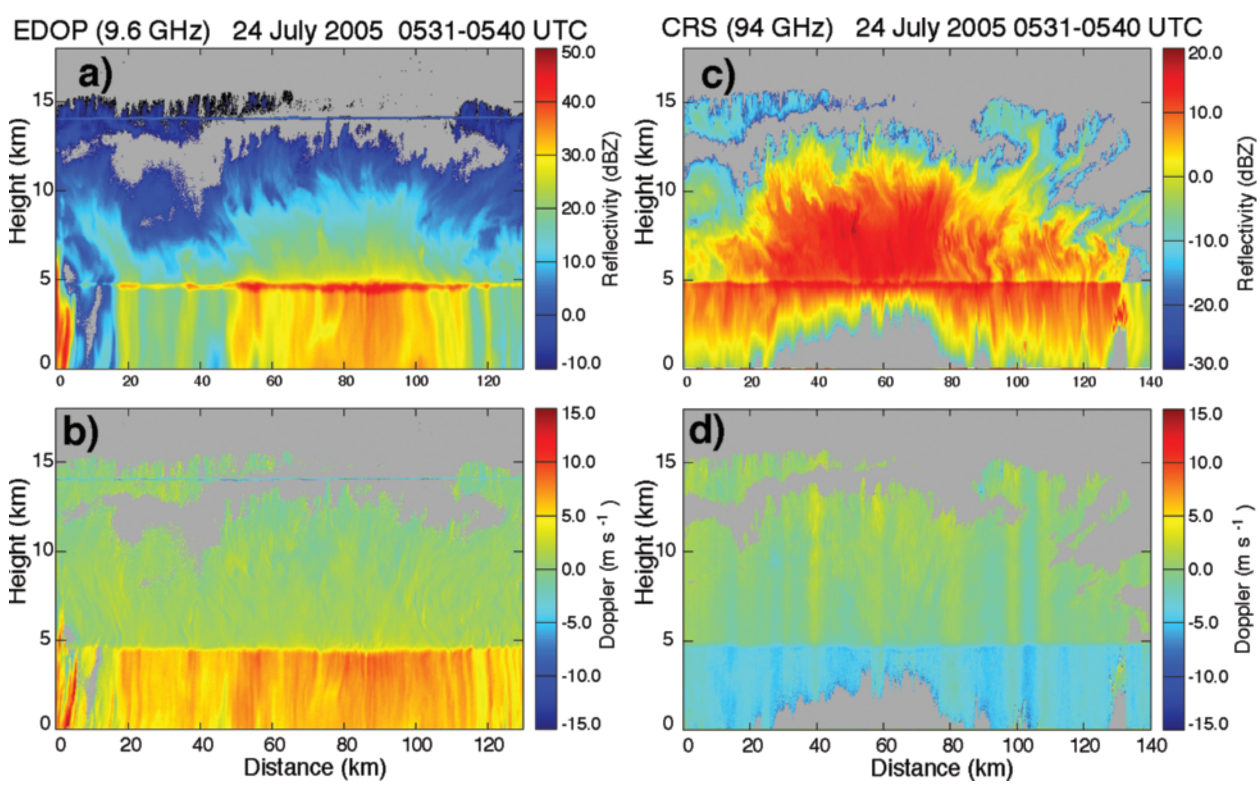

FIG. 11. (a) EDOP vertical reflectivity structure and (b) vertical air motion estimate for the overflight of Tropical Storm Gert's stratiform rain region on 24 Jul 2005. The CRS image of (c) reflectivity and (d) vertical air motions for the same times as the EDOP height–time sections.

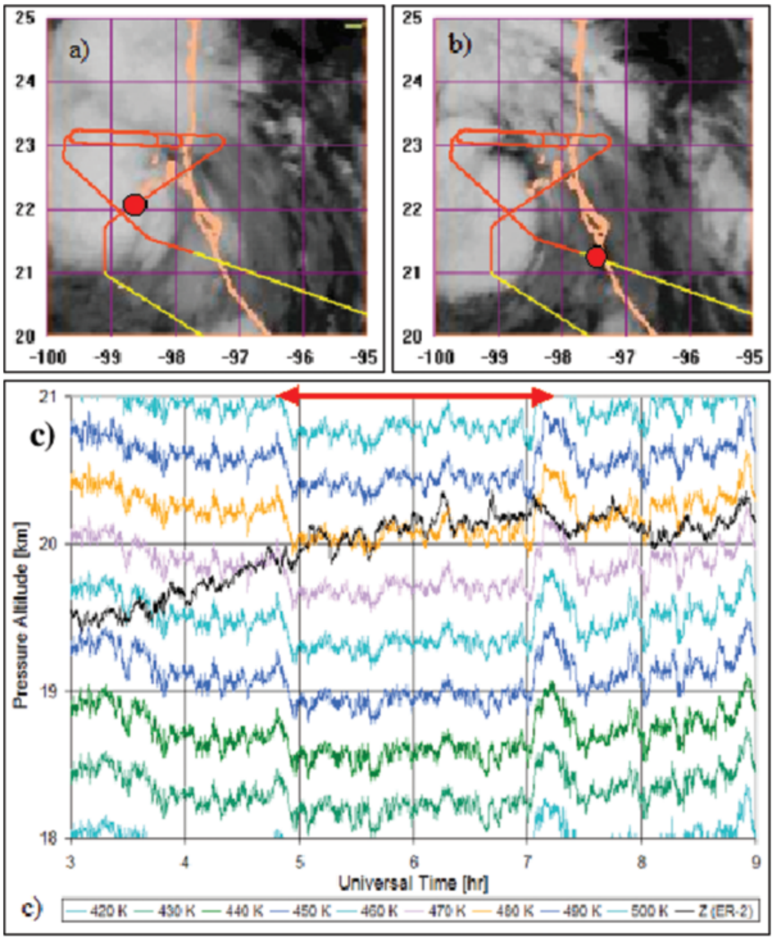

FIG. 12. The ER-2 flight track (yellow) superimposed on infrared cloud images of landfalling Tropical Storm Gert on 25 Jul 2005 at (a) 0500 and 0700 UTC, respectively. The red dot indicates the location of ER-2 at these two times. (c) The isentropes (illustrated in 10-K steps from 420 to 500 K) varying in altitude as a function of time along the ER-2 flight track over Gert. The dipping isentropes between 0500 and 0700 UTC (denoted by the red arrow) imply subsidence over Gert's circulation.

storms and the threat they pose to both property and citizens. The TCSP datasets should improve parameterizations of physical processes contained in the predictive models, with the priority going toward advancing the lead time and forecast skill of hurricane intensity change. TCSP also explored the utility of promising new technologies, such as the Aerosonde UAV, for providing long-endurance monitoring of potential tropical cyclone environments. Data collected within the boundary layer over large fetches of otherwise inaccessible ocean can help fill a critical data void in the initialization of hurricane forecast models. Numerical modeling studies in the Eugene and Gert cases, in particular, initialized with the full suite of TCSP observations (aircraft and satellite), will shed light on these issues.

The TCSP experiment examined some of the outstanding questions of tropical cyclone formation over the western Atlantic. These include 1) the interaction of an easterly wave with the steep terrain of Central America during genesis of a tropical storm; 2) an ongoing study to examine the mesoscale origins of rotation in two named storms, including one in the eastern North Pacific and one in the Caribbean; and 3) the dynamics and evolution of convective bursts in a developing hurricane and a tropical storm. However, the relative importance of regional-scale processes compared to a more universal set of thermodynamic and dynamical genesis interactions on the meso- and convective scales remains to be determined. Additional aircraft-based field experiments on the other side of the physiographically diverse Atlantic basin are needed to address this crucial question.

In the late summer–early fall of 2006, NASA conducted a follow-up experiment investigating tropical cyclogenesis over the eastern Atlantic—the NASA African Monsoon Multidisciplinary Activities (NAMMA-06) campaign. This experiment examined the transition of African easterly waves into tropical depressions in the vicinity of the Cape Verde Islands. It also collected observations on the Saharan air layer to better understand its role during genesis and intensity change. The aerosols and their attendant dry air mass, stable layer, and enhanced vertical shear are all hypothesized to inhibit tropical cyclone growth. When taken together, TCSP and NAMMA-06 should clarify the relative importance of strongly contrasting regional atmospheric influences on Atlantic basin genesis, while at the same time identify those mesoscale events (such as vortex mergers and convective bursts) that constitute a more universal or "core set" of genesis processes.

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REFERENCES

Bister, M., and K. A. Emanuel, 1997: The genesis of Hurricane Guillermo: TEXMEX analysis and a modeling study. *Mon. Wea. Rev.,* **125,** 2662–2682.

Cecil, D. J., E. J. Zipser, and S. W. Nesbitt, 2002: Reflectivity, ice scattering, and lightning characteristics of hurricane eyewalls and rainbands. Part I: Quantitative description. *Mon. Wea. Rev.,* **130,** 769–784.

Chen, S. S., and W. M. Frank, 1993: A numerical study of the genesis of extratropical mesoscale convective mesovortices. Part I: Evolution and dynamics. *J. Atmos. Sci.,* **50,** 2401–2426.

Cotton, W. R., and R. A. Anthes, 1989: *Storm and Cloud Dynamics.* Academic Press, 883 pp.

Davis, C. A., and L. F. Bosart, 2003: Baroclinically induced tropical cyclogenesis. *Mon. Wea. Rev.,* **131,** 2730–2747.

Elsberry, R. L., W. M. Frank, G. J. Holland, J. D. Jarrell, and R. L. Southern, 1987: *A Global View of Tropical Cyclones.* University of Chicago Press, 185 pp.

Emanuel, K. A., 1987: An air–sea interaction model of intraseasonal oscillations in the Tropics. *J. Atmos. Sci.,* **44,** 2324–2340.

Enagonio, J., and M. T. Montgomery, 2001: Tropical cyclogenesis via convectively forced vortex Rossby waves in a shallow water primitive equation model. *J. Atmos. Sci.,* **58,** 685–705.

Gray, W. M., 1968: Global view of the origin of tropical disturbances and storms. *Mon. Wea. Rev.,* **96,** 669–700.

——, 1998: The formation of tropical cyclones. *Meteor. Atmos. Phys.,* **67,** 37–69.

Hendricks, E. A., M. T. Montgomery, and C. A. Davis, 2004: The role of "vortical" hot towers in the formation of tropical cyclone Diana (1984). *J. Atmos. Sci.,* **61,** 1209–1232.

Hennon, P., 2006: The role of the ocean in convective burst initiation: Implications for tropical cyclone intensification. Ph.D. dissertation, The Ohio State University, 185 pp.

Hood, R. E., and Coauthors, 2006: Tropical cyclone precipitation and electrical field information observed by high-altitude aircraft instrumentation. *J. Atmos. Sci.,* **63,** 218–233.

Houze, R. A., Jr., and Coauthors, 2006: The Hurricane Rainband and Intensity Change Experiment: Observations and modeling of Hurricanes Katrina, Ophelia, and Rita. *Bull. Amer. Meteor. Soc.,* **87,** 1503–1521.

Kakar, R., M. Goodman, R. Hood, and A. Guillory, 2006: Overview of the Convection and Moisture Experiment. *J. Atmos. Sci.,* **63,** 5–18.

Kaplan, J., and M. DeMaria, 2003: Large-scale characteristics of rapidly intensifying tropical cyclones in the North Atlantic Basin. *Wea. Forecasting,* **18,** 1093–1108.

Kelley, O. A., J. Stout, and J. B. Halverson, 2004: Tall precipitation cells in tropical cyclone eyewalls are associated with tropical cyclone intensification. *Geophys. Res. Lett.,* **31,** L24112, doi:10.1029/2004GL021616.

Molinari, J., P. Moore, and V. Idone, 1999: Convective structure of hurricanes as revealed by lightning locations. *Mon. Wea. Rev.,* **127,** 520–534.

——, D. Vollaro, and K. L. Corbosiero, 2004: Tropical cyclone formation in a sheared experiment: A case study. *J. Atmos. Sci.,* **61,** 2493–2509.

——, P. Dodge, D. Vollaro, K. L. Corbosiero, and F. Marks, Jr., 2006: Mesoscale aspects of the downshear reformation of a tropical cyclone. *J. Atmos. Sci.,* **63,** 341–354.

Montgomery, M. T., M. E. Nicholls, T. A. Cram, and A. Saunders, 2006: A "vortical" hot tower route to tropical cyclogenesis. *J. Atmos. Sci.,* **63,** 355–386.

Reasor, P. D., and M. T. Montgomery, 2001: Three-dimensional alignment and corotation of weak, TC-like vortices via linear vortex Rossby waves. *J. Atmos. Sci.,* **58,** 2306–2330.

Ritchie, E. A., and G. J. Holland, 1997: Scale interactions during the formation of Typhoon Irving. *Mon. Wea. Rev.,* **125,** 1377–1396.

Rodgers, E. B., S. W. Chang, and H. F. Pierce, 1994: A satellite observational and numerical study of precipitation characteristics in western North Atlantic tropical cyclones. *J. Appl. Meteor.,* **33,** 129–139.

Rogers, R. F., and J. M. Fritsch, 2001: Surface cyclogenesis from convectively driven amplification of midlevel mesoscale convective vortices. *Mon. Wea. Rev.,* **129,** 605–637.

——, and Coauthors, 2006: The Intensity Forecasting Experiment (IFEX): A NOAA Multiyear field program for improving tropical cyclone intensity forecasts. *Bull. Amer. Meteor. Soc.,* **87,** 1523–1537.

Simpson, J., E. A. Ritchie, G. J. Holland, J. Halverson, and S. Stewart, 1997: Mesoscale interactions in tropical cyclone genesis. *Mon. Wea. Rev.,* **125,** 2643–2661.

Simpson, R. H., N. Frank, D. Shideler, and H. M. Johnson, 1968: Atlantic tropical disturbances, 1967. *Mon. Wea. Rev.,* **96,** 251–261.

Steranka, J., E. B. Rodgers, and R. C. Gentry, 1986: The relationship between satellite measured convective bursts and tropical cyclone intensification. *Mon. Wea. Rev.,* **114,** 1539–1546.

Zhang, D.-L., and N. Bao, 1996: Oceanic cyclogenesis as induced by a mesoscale convective system moving offshore. Part II: Genesis and thermodynamic transformation. *Mon. Wea. Rev.,* **124,** 2206–2225.