

# THE PRE-DEPRESSION INVESTIGATION OF CLOUD-SYSTEMS IN THE TROPICS (PREDICT) FIELD CAMPAIGN

## Perspectives of Early Career Scientists

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Early career scientists played crucial roles in the success of the PREDICT field campaign and, in turn, experienced unique career-development opportunities that will shape their research for years to come.

The marsupial paradigm tested by the Pre-Depression Investigation of Cloud-Systems in the Tropics (PREDICT; Montgomery et al. 2012) builds on the notion that a recirculation area may occur in conjunction with tropical disturbances. This recirculation area, or “pouch,” is protected from a potentially hostile environment. Dunkerton et al.

(2009) hypothesized that the pouch is a very favorable area for tropical cyclogenesis because it promotes the accumulation of moisture and cyclonic relative vorticity. As part of its mission to study the structure and environmental conditions associated with tropical disturbances and their pouches, PREDICT involved 26 flight missions into four developing

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and four nondeveloping tropical disturbances in the tropical North Atlantic basin from the island of St. Croix during August and September 2010. PREDICT involved 12 principal investigators (PIs), who represented nine institutions, and more than 70 scientists and support staff. Among the scientific and support staff contributors to PREDICT, no less than 17 were early career scientists (ECSs), defined here as graduate students and postdoctoral researchers. These ECSs represent 11 institutions and come from diverse backgrounds across meteorology and related fields.

Before discussing the roles played by ECSs in PREDICT, it is useful to provide an overview of the roles played by ECSs in previous field campaigns. For brevity, we focus upon field campaigns tangentially related to PREDICT or those studying aspects of tropical meteorology or severe convective storms.

Both the literature and authors' experiences indicate that ECSs have played important roles in numerous previous field campaigns such as the Severe Thunderstorm Electrification and Precipitation Study (STEPS; Lang et al. 2004), the Bow Echo and Mesoscale Convective Vortex (MCV) Experiment (BAMEX; Davis et al. 2004), the Rain in Cumulus over the Oceans (RICO) experiment (Rauber et al. 2007), the Tropical Cloud Systems and Processes (TCSP) experiment (Halverson et al. 2007), and the Tropical Cyclone Structure-2008 (TCS-08) experiment (Elsberry and Harr 2008).

Two more striking examples of ECS involvement in field campaigns within the fields surveyed, however, are given by the Global Atmospheric Research Program (GARP) Atlantic Tropical Experiment (GATE; International and Scientific Management Group for GATE 1974) and the National Aeronautics

## A PI'S PERSPECTIVE ON ECS INVOLVEMENT IN PREDICT

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As in many field projects, students (and, more generally, early career scientists) play a critical part in the planning of missions, the execution of those missions, and the analysis of data (e.g., Rauber et al. 2007). PREDICT was no exception in that regard. Being a project of modest size overall, the involvement of 17 graduate students and postdocs represented a significant fraction of the scientific staff. In many ways, the success of the field phase of PREDICT can be attributed to the efforts of these early career scientists.

What made the involvement of early career scientists in PREDICT distinct were the leadership roles that they assumed in the particularly complex planning and execution of research missions with the G-V aircraft. The needs for PREDICT planning were extensive because of the difficulty in forecasting whether "viable" tropical disturbances would evolve, the expanse of our area of interest, and the multifaceted objectives of the triagency group in the field [National Science Foundation (NSF), NOAA, and NASA].

Most of the forecast products used in the forecasting process for PREDICT were developed by early career scientists, from the marsupial

pouch products to tailored displays of operational model guidance. The prediction of incipient tropical disturbances was not something with which most students were familiar initially. Far greater emphasis is usually placed on the prediction of more mature tropical cyclones, both in the National Hurricane Center and at universities. Thus, students had to rapidly come up to speed on this topic, as well as how to interpret the new forecast tools available. This included tools for interpreting satellite information for nowcasting the location of intense convection during G-V missions.

The expanse of the PREDICT domain of interest, essentially the entire tropical and subtropical Atlantic as well as the Caribbean Sea, meant that there were often multiple disturbances to consider. Weather briefings had to be inclusive but still delivered within 30 min. Furthermore, the variety of objectives of NOAA, NASA, and NSF participants meant that not just nascent tropical disturbances but also tropical cyclones in all stages of evolution had to be scrutinized. This proved particularly challenging in 2010 when there were 11 named storms during the 46 days of PREDICT. The clarity and information content of the briefings offered by the PREDICT

early career scientists was uniformly high. Furthermore, the responsiveness of forecasts and nowcasters to PI inquiries, either in planning or during operations, contributed greatly to the success of the project.

Equally important to weather briefings and nowcasting in support of the aircraft missions was monitoring the data collected by the G-V, both on board and in the operations center. A singular point of responsibility lay with the initial quality control of the dropsonde data prior to their dissemination to operational weather prediction centers through the Global Telecommunications System (GTS). These data were assimilated into the ECMWF model (among others) and were seen to have a significant influence on subsequent forecasts (which, in turn, benefited our mission planning activities).

Finally, and perhaps most importantly, students were fully engaged in science discussions (and debates) about interpretations of what the atmosphere was doing and why. These discussions may prove to be the most influential aspects of the involvement of early career scientists from the standpoint of their future research directions and the subsequent research of the PIs as well.

and Space Administration (NASA) African Monsoon Multidisciplinary Analyses (NAMMA; Zipser et al. 2009) program. During GATE in 1974, approximately 50 ECSs from multiple institutions played vital roles on board both ships and aircraft (E. Zipser 2011, personal communication) that enabled the mission to successfully collect data that has significantly advanced our collective understanding of tropical meteorology. Many of the ECSs involved in GATE are now leaders of the field at academic institutions, operational forecast centers, and national research centers. Similarly, during its 2006 study of the Saharan air layer and developing and nondeveloping tropical disturbances, NAMMA featured ECSs from 10 institutions that served primarily in forecasting and aircraft support roles. Data collected during NAMMA has formed and continues to form the basis for research conducted in part by ECSs, particularly by ECSs of underrepresented backgrounds at institutions in the United States and Senegal (Zipser et al. 2009, and references therein; Jenkins and Gaye 2010).

In PREDICT, similar to NAMMA, ECSs served numerous roles critical to the success of the field campaign. These roles include lead and assistant forecasters, flight support operators, and data processors and analysts. In these roles, ECSs were responsible for providing forecasts that determined mission targets, developed flight patterns, and kept missions out of potentially troubling situations once airborne; developing novel products for both operational and research purposes; and processing data in real time for use in the decision-making processes of both PREDICT and the National Hurricane Center (NHC). Even after the program's conclusion, many of the ECSs plan to use the data gathered during PREDICT as part of their graduate work or early career research, studies that will hopefully provide meaningful contributions toward our understanding of the tropical cyclogenesis process in the future.

In addition to the contributions made by ECSs to PREDICT, the experiences that ECSs gained while in the field have already proven and likely will continue to prove crucial to their career and personal development. ECSs were granted networking, scientific discussion, and applied learning experiences that a classroom is unable to provide. In addition, the skills acquired during PREDICT will enable the involved ECSs to potentially lead future field campaigns of their own to study priority problems in and beyond tropical meteorology. Despite the level of involvement of ECSs within previous field campaigns in the field surveyed and the atmospheric sciences as a whole, however, there is little evidence in the

literature documenting these roles and the benefits gained from such involvement to both the ECSs involved and the field program itself. Therefore, the important contributions of ECSs to PREDICT and the career-development experiences obtained therein are detailed within this manuscript. We start with the contributions and experiences of the forecast team.

*Forecasting operations.* ECSs made essential contributions to PREDICT field campaign as forecasters. Of the 10 scientists serving as PREDICT forecasters, 3 were postdoctoral fellows (Evans, Galarneau, and Tang) and 4 were graduate students (Archambault, Cordeira, Griffin, and Sears). During the final third of the field campaign, the forecast team, including the position of lead forecaster, was entirely composed of ECSs. Rather than functioning primarily as support for senior scientists, ECSs took on leadership roles by giving the majority of the briefings and discussions.

During PREDICT, forecasters were responsible for presenting daily 1400 UTC internal weather briefings upon which the PREDICT PIs and mission scientists based mission planning decisions. The primary aim of the forecasters during this briefing was to convey the expected position, likelihood of development, and associated forecast confidence of incipient tropical disturbances expected to be located within the PREDICT geographical domain. Forecasters began every briefing with a short overview of the current synoptic-scale features of interest across the North Atlantic basin. An example of an annotated synoptic overview presented at the outset of an internal briefing is shown in Fig. 1.

Following the synoptic overview, PREDICT forecasters spent approximately 10–20 min providing synopses of the current environmental conditions and mesoscale structure associated with each tropical disturbance. During this part of the briefing, forecasters made ample use of the University of Wisconsin's Cooperative Institute for Meteorological Satellite Studies (CIMSS) PREDICT web page, where satellite-derived fields such as lower-tropospheric relative vorticity and deep-layer vertical wind shear were interactively overlaid with satellite imagery or other data. Particular emphasis was placed on the presence or absence of sustained deep, moist convection close to the center of the disturbance. This was evaluated using radar imagery (if available), conventional and microwave satellite imagery, and satellite-derived products highlighting the frequency and occurrence of deep convection in the vicinity of the disturbance (e.g., overshooting tops; see "Real-time and research product generation" section). If a mission

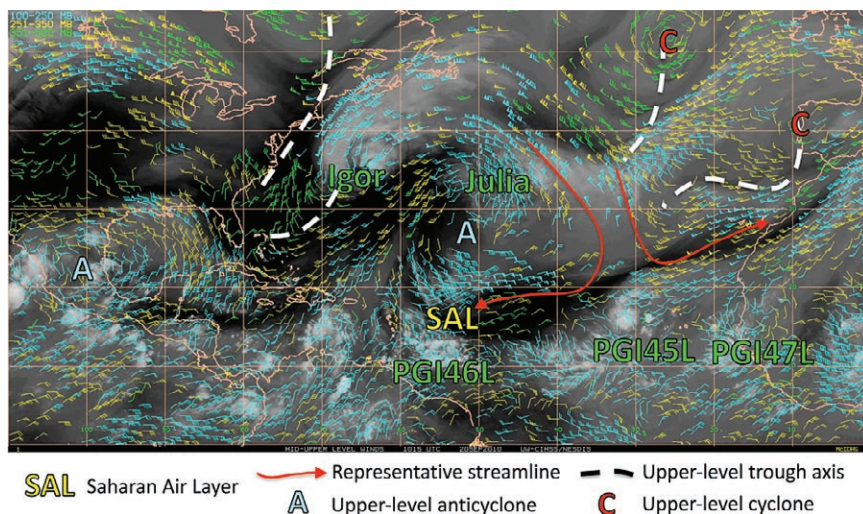
was ongoing during the morning weather briefing, dropsonde wind data obtained from the mission in progress often were overlaid on infrared imagery in real time so that forecasters could convey the current three-dimensional kinematic, thermodynamic, and convective structure of the disturbance.

After the synopsis of each feature was complete, forecasters spent approximately 10–20 min discussing the track and development scenarios for each disturbance for the next two days. In addition to presenting deterministic fields highlighting forecast pouch track and intensity, the forecasters made extensive use of global and mesoscale ensemble model output (e.g., spread and probability distribution functions of relevant meteorological fields) to illustrate forecast uncertainty in the position and intensity of a given disturbance of interest. Given the geographical limits of the PREDICT domain and the substantial airspace restrictions over the Caribbean Sea (see also “Meteorological overlay fields” section), conveying

the degree of forecast uncertainty in the disturbance position over the following two days was of critical importance to the PREDICT team. A second key component of this portion of the briefing was conveying the probability of the disturbance being unsuitable for a flight mission due to either its dissipation or intensification to tropical cyclone strength.

At the conclusion of the briefing, the PIs used the information presented as a basis for deciding the preliminary flight plans for the next two days. The decision process included discussion of which disturbance, if any, would be targeted and what flight pattern was most appropriate to survey them. During this part of the weather briefing, considerable interaction took place between the PIs and the forecasters. Forecasters were often called on to pinpoint forecast tropical disturbance locations to help PIs devise flight plans, incorporating the aforementioned airspace restrictions and inherent uncertainty in the locations and intensities of these features.

In addition to the PREDICT internal weather briefing, PREDICT forecasters were responsible for leading the daily 1600 UTC triagency weather discussion during three periods of the campaign (16–22 August, 6–12 September, and 27–30 September 2010). The daily triagency weather discussions were presented to the three active field programs: PREDICT, the National Oceanic and Atmospheric Administration (NOAA) Intensity Forecasting Experiment (IFEX; Rogers et al. 2006), and the NASA Genesis and Rapid Intensification Processes (GRIP; <http://grip.nsstc.nasa.gov/>) field campaign. These weather discussions generally lasted only 20–30 min but had a broader discussion focus than the PREDICT internal weather briefings because of the different research foci of each field program.



**FIG. 1.** University of Wisconsin CIMSS Geostationary Operational Environmental Satellite-13 (GOES-13)/Meteosat-9 merged water vapor satellite imagery overlaid with middle-to-upper-tropospheric cloud-track winds (barbs; half barb = 5 kt; full barb = 10 kt; pennant = 50 kt, shaded by pressure altitude per the legend at top left) valid at 1015 UTC 20 Sep 2010. Salient upper-tropospheric features of interest are subjectively analyzed on this image and labeled per the legend at the bottom of the diagram. In this example, there are five tropical disturbances of interest: Hurricane Igor near Bermuda; Tropical Storm Julia near 32°N, 50°W; the future Hurricane Lisa (dubbed PGI45L) near the Cape Verde Islands; the future Tropical Storm Matthew (dubbed PGI46L) near the Lesser Antilles; and a nondeveloping disturbance (dubbed PGI47L) along the west coast of Africa. Note that PGI stands for PREDICT–GRIP–IFEX, the three concurrent field campaigns studying tropical cyclone formation and rapid intensification in the tropical North Atlantic basin (the “L” in PGIxxL) during Aug and Sep 2010. PREDICT ECS forecasters often created and utilized images such as this to convey the features of interest across the North Atlantic basin and, in conjunction with a previous day’s worth of images, to highlight how the synoptic-scale weather pattern was evolving.

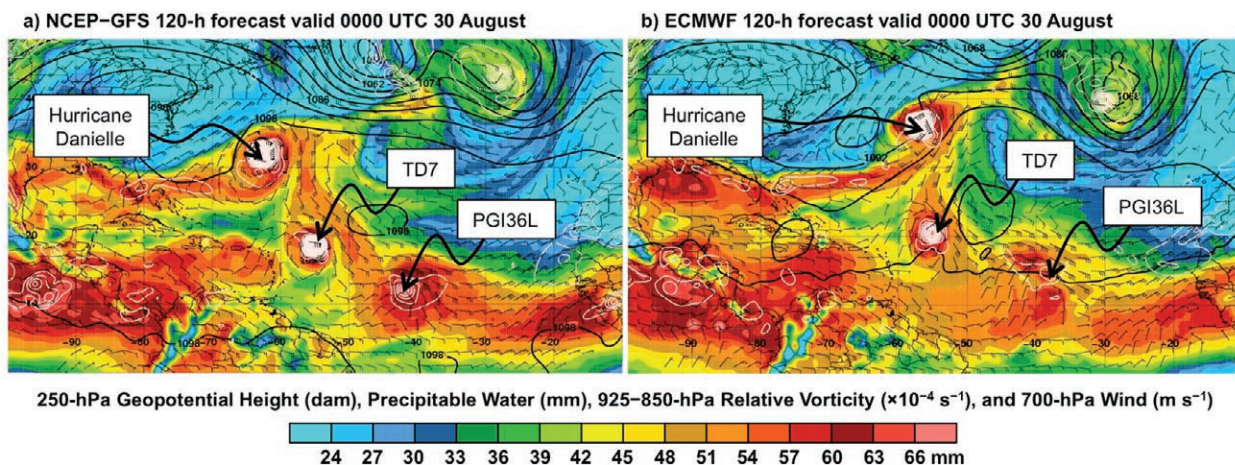
With the exception of day 1, at least one ECS presented during every internal briefing and triagency discussion. In addition, throughout PREDICT, at least one ECS was involved daily in collaborating with PIs on flight patterns both prior to and during missions. Furthermore, ECSs prepared most of the comprehensive documentation of the internal briefings and triagency weather discussions found in the online PREDICT field catalog (<http://catalog.eol.ucar.edu/predict/>).

The benefits of ECS involvement as forecasters were not limited to the advancement of the field program's goals, however. Through their interactions with other ECSs and the PREDICT PIs and mission scientists, ECSs were able to gain substantial forecasting and scientific analysis skills. Further, given the relatively short (30–60 min) lengths of the forecast briefings, ECSs were also able to learn how to effectively give comprehensive yet concise scientific discussions. Serving as forecasters was not the only forecast- and analysis-related means by which both ECSs and PREDICT benefited from ECS involvement, however. ECSs created a number of real-time and research analysis products that were available to forecasters during PREDICT. These are described next.

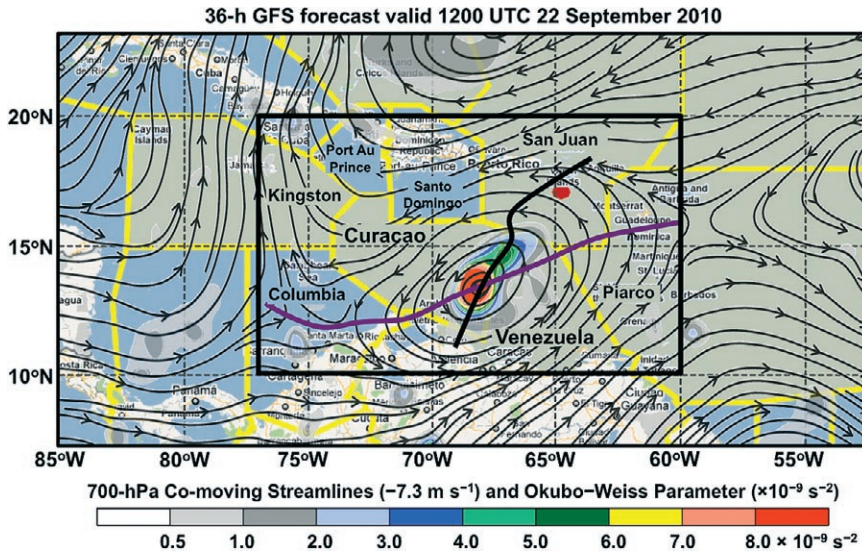
*Real-time and research product generation.* As noted above, a number of ECS-created forecast and analysis products helped to support the forecast team and scientific mission of PREDICT. Examples of such

products include large-scale analyses of meteorological fields believed to be of importance to the tropical cyclone formation process, overlays of these and other fields on top of flight preparation information, satellite-based estimates of the locations of tropopause-penetrating convection, and analyses of the flow fields associated with model-analyzed areas of potential tropical cyclogenesis events. Each of these is described in further detail below.

*LARGE-SCALE ANALYSES.* One of the goals of ECS participation during the weather-briefing portion of the PREDICT field campaign was to provide and disseminate real-time weather products to the PREDICT PIs and mission scientists. To aid in this process, ECSs created unique forecast products from gridded data obtained from multiple numerical forecast models to complement and expand on existing resources. Examples of meteorological analyses generated, maintained, and updated by ECSs during PREDICT include those of isentropic potential vorticity, basin wide Okubo–Weiss parameter and storm-relative streamlines, total precipitable water (TPW), and relative vorticity. These unique forecast products displayed information relevant to specific PREDICT science objectives (e.g., Montgomery et al. 2012) and were chosen to provide a comprehensive yet concise overview of the forecast structure of each tropical disturbance across the North Atlantic basin and its environment. An example of one such analysis is



**FIG. 2.** ECS-generated forecast comparison product depicting precipitable water (shaded; mm), 250-hPa geopotential heights (solid black contours; dam), 925–850-hPa cyclonic relative vorticity (solid white contours every  $0.5 \times 10^{-4} \text{ s}^{-1}$  starting at  $0.5 \times 10^{-4} \text{ s}^{-1}$ ), and 700-hPa wind (half barb =  $2.5 \text{ m s}^{-1}$ ; full barb =  $5.0 \text{ m s}^{-1}$ ; pennant =  $25.0 \text{ m s}^{-1}$ ) for (a) the NCEP GFS and (b) the ECMWF 120-h forecasts valid at 0000 UTC 30 Aug 2010. This product simultaneously provided information regarding the forecasted environments and locations of features of potential interest to the objectives of PREDICT. In this example, such features include Hurricane Danielle, Tropical Depression 7 (TD7; which later became Hurricane Earl), and disturbance PGI36L (which later became Tropical Storm Fiona).



**FIG. 3.** 0000 UTC 21 Sep 2010 GFS 36-h forecast of 700-hPa streamlines (thin black lines) and Okubo-Weiss parameter (shaded, units:  $\times 10^{-9} \text{ s}^{-2}$ ) in the co-moving framework. The “critical latitude” (e.g., Dunkerton et al. 2009) is depicted by the light purple line, whereas the wave axis is denoted by the thick black line. Flight information region (FIR) boundaries are depicted by the thick yellow lines. The map background is provided by Google Maps. In this example, depicting what would become Tropical Storm Matthew, the 36-h forecast suggests that the disturbance will be located within Curacao air space, for which PREDICT had flight clearance, but that the eastern portion of the disturbance would be located near Venezuelan airspace, for which PREDICT and GRIP had their initial flight clearances revoked during an early scientific mission. Such a scenario required mission scientists and ECSs to carefully craft the next day’s flight path and radiosonde drop pattern.

depicted in Fig. 2. Creating these products allowed additional ECSs to assist the forecast process and to refine tools that may become or are already a part of their own research and/or operational tropical cyclone forecast product suites.

**METEOROLOGICAL OVERLAY FIELDS.** For forecasters and PIs during PREDICT, identifying a feature of interest was often the easiest of their many tasks. Conversely, determining whether such a feature could be reasonably sampled by a research mission posed numerous logistical hurdles, particularly given numerous airspace restrictions across the Caribbean Sea. If a given disturbance was forecast to be located in an area that could not be flown into, modifications to the



**FIG. 4.** The NCAR EOL mission coordinator display valid at 1804 UTC 14 Sep 2010, depicting the planned (red) and actual (maroon) tracks of the aircraft during a research flight into developing Tropical Storm Karl. Regions of lightning activity are denoted by the negative signs, whereas objectively identified overshooting tops are denoted by the large solid squares. For reference, the Yucatan Peninsula is depicted

at the left portion of the image. In this example, the aircraft (denoted by the aircraft symbol) is diverting its path to the south of a region of deep convection and intense lightning activity. ECSs on flight support operations and mission coordinators on board the aircraft received this product in real time, allowing for them to assist the pilots in diverting such potentially damaging convection well before it could become a problem.

flight track and/or decision to fly had to be made. To assist in this process, ECSs developed unique overlay products that combined meteorological forecasts with flight boundary and geographic information; an example of which is given in Fig. 3.

The creation of such products served multiple purposes for both ECSs and PREDICT as a whole. These products allowed for mission scientists and PIs to determine the flight track for the next day's mission as well as plan future flight schedules based upon flight clearance and crew rest requirements. In addition, independent of the flight clearance logistics, such products were used by mission scientists to help make critical decisions related to a potential evacuation of the PREDICT operations center in advance of Hurricane Earl in late August 2010 (see "Hurricane Earl evacuation preparation" sidebar). For ECSs, creating these products allowed them to gain a better appreciation for the forecast evolution of features of interest, gain familiarity with the logistics of the flight planning process, and assist mission scientists in making flight and radiosonde drop pattern decisions.

**SATELLITE-BASED ANALYSES.** Once a forecast had been made, an appropriate flight path had been drawn,

and a research mission had become airborne, of primary importance to the mission was the safety of the aircraft and its crew. Monitoring the safety of the aircraft and its crew required continual monitoring of convective activity near and along the projected flight path of the aircraft. Not all convective activity was of equal significance to the safety of the aircraft and its crew, however. Rather, the crew on board the aircraft was most interested in areas of intense lightning activity and potential turbulence, often coincident with convection that is "overshooting" (or penetrating) the tropopause. To that end, one of the ECSs involved in PREDICT (Monette) modified an algorithm developed by Kristopher Bedka (Science Systems and Applications, Inc.) to enable the monitoring of deep tropical convective activity, which is dubbed here as "overshooting tops," based upon the nature of the top of the convective towers. An example of this product is given in Fig. 4, whereas more detailed information on the product can be found online (at [http://cimss.ssec.wisc.edu/tropic2/predict/overshooting\\_tops/](http://cimss.ssec.wisc.edu/tropic2/predict/overshooting_tops/)). This product was used in real time by other ECSs in flight support operations to help maintain the safety of the aircraft and its crew while maximizing a mission's scientific objectives.

## HURRICANE EARL EVACUATION PREPARATION

**A**s PREDICT entered its second week of field operations in St. Croix in late August, the approach of Hurricane Earl caused quite the stir among the field campaign participants. From the time when it first became a classified tropical cyclone in 25 August 2010, the official NHC forecast suggested that Earl could approach St. Croix on 30 August 2010 as a Saffir–Simpson scale category 2 or 3 hurricane. This forced the project managers of the NCAR EOL to consider an evacuation of the NCAR G-V aircraft and all or portions of the scientific and support staff in advance of Earl's arrival. Although much of the decision-making process involved collaborative discussions between PREDICT PIs and EOL staff, the two ECS forecasters on station at the time (Cordeira and Griffin) were instrumental in obtaining and disseminating the necessary forecast information so that the appropriate evacuation decisions could be made.

Starting on 26 August, the PREDICT ECS forecast team was tasked with determining the likelihood of Earl directly or indirectly impacting St. Croix. Forecasts relied heavily upon the dissemination of National Hurricane Center probabilistic products, including the "cone of uncertainty" and graphical wind speed exceedance probability products (e.g., [www.nhc.noaa.gov/archive/2010/EARL\\_graphics.shtml](http://www.nhc.noaa.gov/archive/2010/EARL_graphics.shtml)). These efforts culminated in a special ECS-led afternoon weather briefing on 28 August 2010, during which the decision was made to evacuate the aircraft from St. Croix to Barbados on Sunday, a day prior to Earl's anticipated arrival, while only issuing a voluntary evacuation for other personnel. While Earl passed approximately 150 km to the north of St. Croix as a Saffir–Simpson scale category 4 hurricane, wind gusts estimated to hurricane force were felt at the PREDICT operations center on the north side of St. Croix with damage across the U.S. Virgin Islands estimated

at in excess of \$2.5 million U.S. dollars (VITEMA 2010). Thus, despite a feeling of unease prior to Earl's arrival, the collaborative decision made by EOL staff and PREDICT PIs with the assistance of PREDICT ECSs arguably turned out to be the right one.

For the ECSs involved, these discussions provided a unique opportunity to help lead a group toward a decision where tens to hundreds of thousands of dollars could be spent based upon what decision was made. Being in the proverbial "hot seat," where information was stated on the record and all uncertainties must be accounted for, was quite the burden. Their involvement in the decision-making process for an evacuation in advance of Hurricane Earl was something that could not have been foreseen prior to PREDICT. However, it nevertheless exemplifies how ECSs were vital to the success of PREDICT and how, in turn, PREDICT provided invaluable real-world career-development experience to the ECSs involved.

Though the overshooting top product had been utilized in another experiment prior to PREDICT (the NOAA Hazardous Weather Testbed Spring Experiment), PREDICT was the first program in which it was used in real time for critical mission coordination purposes. In addition, PREDICT was the first time in which an ECS—rather than a research scientist—was directly responsible for the generation of the product in real time. Beyond the utilization of the product in real time, these data will be used by Monette as part of her master’s thesis to evaluate their utility in forecasting tropical cyclogenesis, thus providing an observational test toward critically evaluating the “vortical hot tower” theory for tropical cyclogenesis (Montgomery et al. 2006).

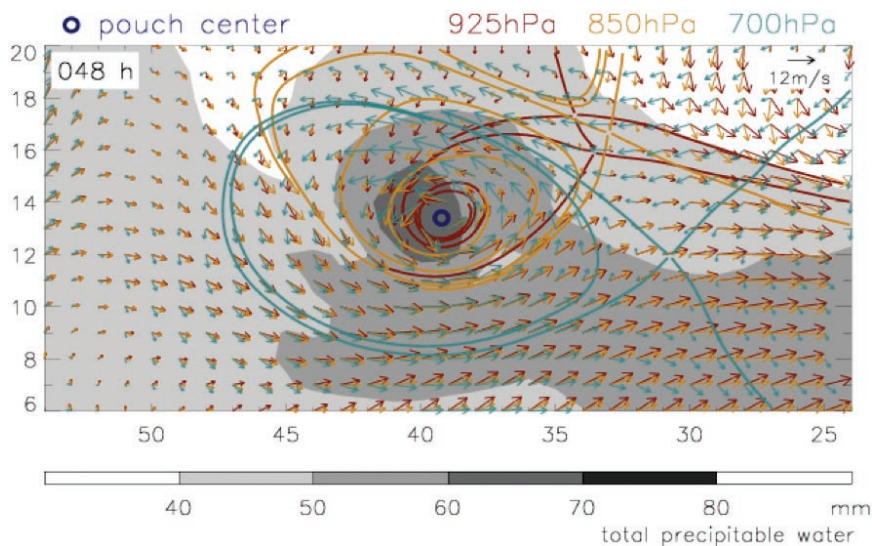
*Evaluating model-derived disturbance flow fields.* ECSs were also involved in developing products that helped support PREDICT forecast operations by evaluating the structural evolution of the tropical wave and its

accompanying pouch in the marsupial framework. One such example is given by analyses of the numerical model-derived flow fields associated with tropical disturbances and their accompanying pouches.

In the frame of reference moving with the tropical wave, here termed the co-moving frame, the flow usually evolves slowly and it is reasonable to approximate the flow as steady. Streamlines in this co-moving frame thus indicate air parcel trajectories. For steady flow, closed streamlines identify recirculation areas. Streamlines that emanate from the flow’s hyperbolic stagnation points, so-called manifolds, are helpful to divide the flow into distinct regions (e.g., those associated with the tropical wave and the external environment). In particular, a closed manifold demarks the outer bound of a recirculation area (e.g., the closed manifold at 700 hPa in Fig. 5). If there is net convergence within the recirculation area, the manifold slowly spirals inward, indicating slow entrainment of air from the environment into the pouch (e.g.,

the manifold at 850 hPa in Fig. 5). It is hypothesized that examination of the manifolds provides useful information about pouch structure and evolution.

A forecast product based on the above ideas, informally referred to as the dividing streamline product, was developed and implemented in real time by one of the authors (Riemer) and colleagues at the Naval Postgraduate School. The main purpose of this product is to display the pouch’s vertical structure by overlaying manifolds at different levels. The manifolds were calculated for each tropical disturbance in the co-moving frame of reference under the assumption of layer-wise horizontal flow and were calculated using data from the 0000 UTC runs of four global weather forecast models [the European Centre for Medium-Range Weather Forecasts (ECMWF), the Global Forecast System (GFS), the



**FIG. 5.** Manifolds (bold lines; loosely referred to as dividing streamlines) and horizontal winds (vectors;  $\text{m s}^{-1}$  with reference vector at top right) at 925 (red), 850 (yellow), and 700 hPa (blue) valid at 0000 UTC 30 Aug 2010 from the 0000 UTC 28 Aug 2010 run of the ECMWF model for the predecessor disturbance of Tropical Storm Fiona. The horizontal axis is in degrees west longitude and the vertical axis is in degrees north latitude. In this example, a virtually closed recirculation region is evident at 700 hPa. The inward spiraling of the manifolds at 850 and 925 hPa indicate weakly convergent flow at these levels. The manifolds indicate that, at 850 hPa, most of the very dry air in the northwest (TPW < 40 mm) will be deflected to the south and stay outside of the pouch. Dry air to the northwest with TPW between 40 and 50 mm is located within the pouch at this level and may slowly converge toward the pouch center. Furthermore, the product highlights the vertical pouch structure. Here, the pouch is not in complete vertical alignment: the recirculation area depicted by the manifolds at 700 hPa extends  $2^{\circ}$ – $3^{\circ}$  farther to the south than at 850 hPa, and at 850 hPa the recirculation area extends  $2^{\circ}$  farther to the north than at 700 hPa.



Navy Operational Global Atmospheric Prediction System (NOGAPS), and the Met Office (UKMO)]. The product was available to forecasters in time to prepare the morning forecast briefings. Details on the calculation of the manifolds and an analysis of their structure and relevance for a mature tropical cyclone in an idealized numerical experiment can be found in Riemer and Montgomery (2011).

An example of one of the real-time dividing streamline forecast products is presented in Fig. 5. Such products were used frequently by ECSs in the morning weather discussions. Although the assumptions of steady and two-dimensional horizontal flow do not always hold, the product proved helpful to discuss the potential of dry air entrainment into the pouch region and to aid in determining the next day's preliminary flight pattern. Furthermore, the variability of the vertical pouch structure emphasized by this product highlights the importance of sampling the vertical moisture and wind distribution around an incipient tropical cyclone. To that end, kinematic and thermodynamic data gathered from multiple missions during PREDICT will be used in the future to better understand the evolution of tropical disturbance pouches and how they are influenced by the external environment.

**FLIGHT SUPPORT OPERATIONS.** In addition to their roles in supporting forecast operations, ECSs served crucial roles as nowcasters while missions were ongoing. As alluded to in the discussion of the overshooting tops product, communication between the operations center and the flight crew was important for real-time decision making in convectively active regions. This decision making was facilitated by ECSs monitoring the latest data being fed into the operations center via the "mission coordinator" display software (e.g., Fig. 4). Using this software, the primary task of the ECS in charge of flight operations was to monitor hazardous weather along the flight path using infrared satellite imagery, the overshooting tops product, and lightning data. If hazards were detected near or ahead of the plane, the ECS informed the mission scientist so the pilots could be warned with sufficient lead time to modify their course.

Oftentimes, the mission scientist also requested additional data not readily available on the plane, including visible satellite imagery or land-based radar data, to fine-tune their decisions on whether to divert or proceed as planned. The ECS was to find the most recent imagery and send it directly to the mission scientist or to work with the mission coordinator display programmer to make available

overlays of such products to the flight crew. This additional data helped the pilots and mission scientists determine the feasibility of a flight path with much higher confidence. In addition, the mission coordinator display also allowed dropsonde data to be plotted at specific levels upon being processed by another ECS. Thus, ECSs were often the first to alert other PREDICT scientists of the structure of the disturbance as it was being sampled.

Finally, ECSs provided input when it became necessary to modify flight patterns during a mission in order to better sample a tropical disturbance and its pouch. For instance, on the last day of the field campaign, there was high uncertainty regarding the location of the targeted disturbance due to its disorganization and large spread in the available model guidance. The science director and the ECSs collaborated while the day's mission had begun to execute drops. After evaluating the early dropsonde data in conjunction with satellite imagery, a decision was made to shift the flight path a few degrees east. In retrospect, this yielded a more complete sampling of what would become Hurricane Otto several days after the conclusion of PREDICT. In all, ECS forecasters, developers, and nowcasters each played integral roles in the planning and execution stages of the 26 missions flown during PREDICT. However, helping to plan a mission and steer it clear of unfavorable weather was only half the battle. The other half came from the data collection and analysis process.

**INSTRUMENTATION.** Of the multiple datasets collected during PREDICT (Montgomery et al. 2012), two of these featured substantial ECS involvement: dropsonde data and water vapor data derived from global positioning systems (GPSs). As is discussed below, ECSs were integral to the collection of both sets of data.

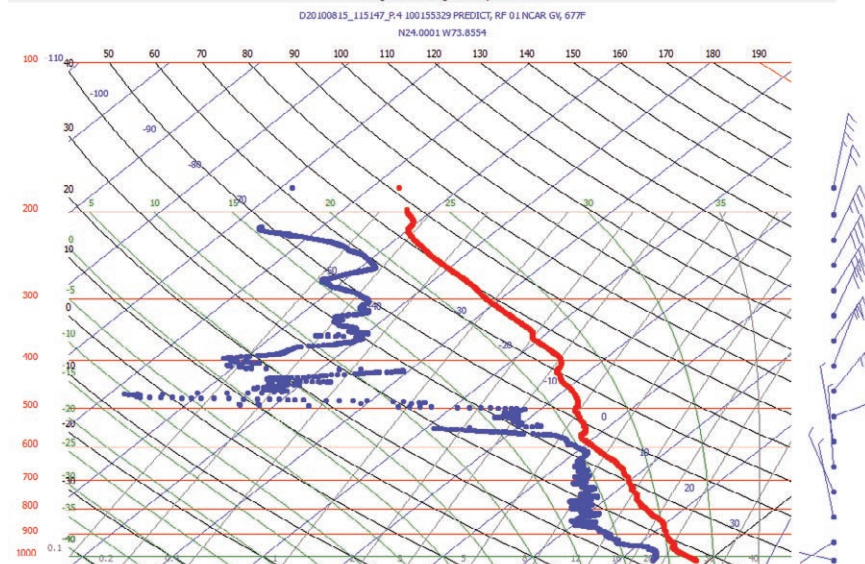
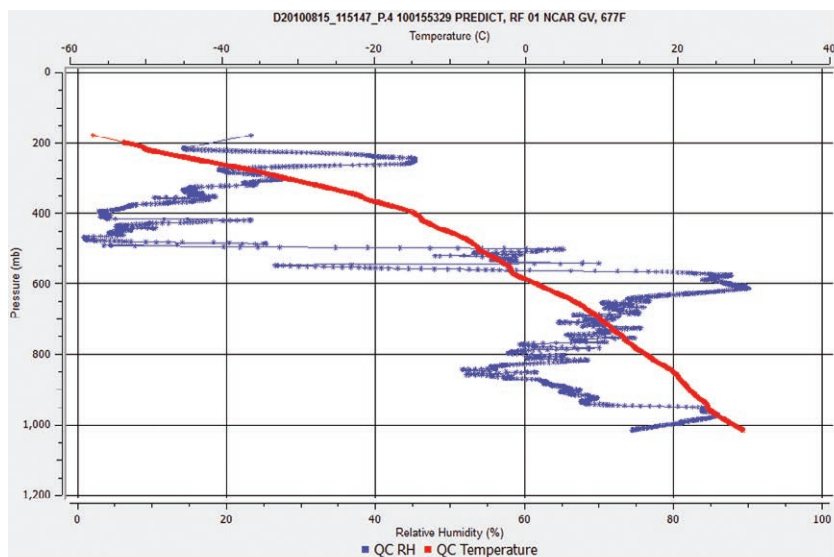
*Dropsondes: Data collection, processing, and analysis.* During PREDICT, three ECSs (Komaromi, Stern, and Thompson) served as dropsonde assistants (DAs). Utilizing the Atmospheric Sounding Processing Environment (ASPEN) software, DAs were tasked with the processing and quality control (QC) of dropsonde data obtained from the more than 500 dropsondes released during PREDICT. The processing and QC of these data were performed in real time, helping to guide the PIs in their decisions as to sampling times and locations. This real-time processing also allowed the dropsonde data to be assimilated into the various global weather forecast models to potentially improve

the predictability of tropical cyclogenesis and to be used by National Hurricane Center forecasters to gauge the structure and intensity of incipient tropical disturbances (e.g., NHC 2010).

The DAs used ASPEN to perform QC on the raw data files that were first uploaded from the aircraft to a server on the ground. An example of a DA-processed sounding from one of PREDICT's missions is depicted in Fig. 6. Because ASPEN is a largely automated processing tool, the primary task of the DAs was to examine both the raw and quality-controlled data and thus ensure that ASPEN was performing correctly. Although often ASPEN did exactly what it was designed to do, there were a few cases where sondes were not correctly processed by the software. This required human intervention and the DAs made use of their meteorological

knowledge to diagnose and, in many cases, rectify these problems.

For example, bad temperature data would occasionally not be removed by ASPEN. The DA thus had to either manually flag such points in the raw data prior to reprocessing with ASPEN or delete the contaminated significant levels from the data. Other problems arose with sondes that fell faster than they should because of malfunctions in parachute deployment. Because the dynamic corrections applied by ASPEN to the dropsonde data depend upon the fall speed, automated processing of these data occasionally led to errors. The DA had to make a decision as to whether a given sonde fell faster than it should have, taking into account the fact that large sonde vertical velocities could instead be due to updrafts and downdrafts in convection. Additionally, the dropsonde launch

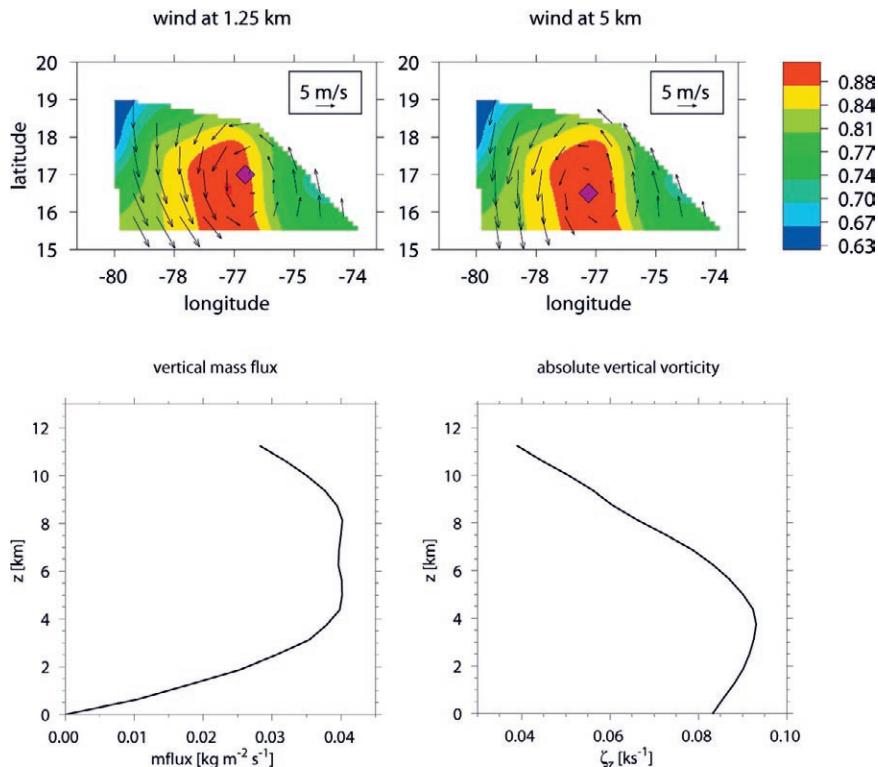


**FIG. 6. (top)** Quality-controlled vertical profiles of temperature (thick red line; units in °C; top axis) and relative humidity (thin blue line and marks; units in %; lower axis) at 24.0°N, 73.85°W from a dropsonde released at 1151 UTC 15 Aug 2010 during PREDICT's first research flight. In this example, obtained from the environment of a nondeveloping disturbance along a remnant frontal boundary, the layer between 600 and 1,000 hPa is relatively dry with relative humidity between 60% and 80%. The middle to upper troposphere above 600 hPa is very dry with relative humidity generally below 40%. **(bottom)** Quality-controlled skew T diagram of temperature (thick red line; units in °C), dewpoint (thick blue line; units in °C), and winds (blue barbs; half barb = 5 kt; full barb = 10 kt) from the same dropsonde described above. In addition to the dryness noted above, this profile exhibits a hostile 35–40 kt of easterly vertical wind shear. ECSs continually quality-controlled and manually reviewed dropsonde data, such as these in real time during PREDICT research missions.

7 Jan 2011 17:28 UTC

system itself occasionally incorrectly detected a launch while the sonde was still inside of the aircraft. This led to the recording of raw winds near the top of the sounding that were of about the same magnitude as the speed of the airplane and prevented the accurate processing of the entire sounding. DAs were able to reprocess the otherwise good sonde with ASPEN once these erroneous data were removed. Finally, even once a dropsonde had been correctly processed by ASPEN, formatting issues arose between the ASPEN software and the program used to transmit the data across the network to the National Center for Atmospheric Research (NCAR) Earth Observing Laboratory (EOL) as well as to the World Meteorological Organization. DAs thus had to manually correct each transmission to ensure that the data were properly formatted for later ingestion by global numerical weather prediction models.

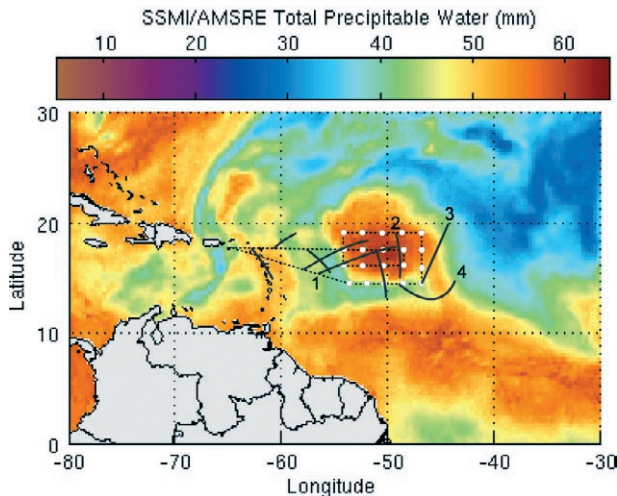
PREDICT flight operations also provided ECSs with the opportunity to participate in research flights aboard the NCAR Gulfstream V (G-V) aircraft. This afforded DAs and other ECSs the opportunity to deploy multiple dropsondes during multiple missions. Deploying a dropsonde required preparing, arming, and launching the dropsonde. Before it could be launched, each dropsonde had to be unpacked from its casing and have its parachute extended outward from the point at which it is attached to the dropsonde. If care were not taken in this procedure, the parachute could potentially become entangled during the launch, resulting in the dropsonde falling too quickly and thus impacting data quality. Once the dropsonde was activated and communications between it and the aircraft were



**FIG. 7.** Analyses from the 13 Sep 2010 research flight into the disturbance that would later become Hurricane Karl. (top) Wind field in the co-moving reference frame (vectors;  $\text{m s}^{-1}$  with the reference vector at top right) and saturation fraction (shaded; nondimensional) at (top left) 1.25 and (top right) 5.0 km above mean sea level. (bottom) Spatially averaged (bottom left) vertical mass flux ( $\text{kg m}^{-2} \text{s}^{-1}$ ) and (bottom right) absolute vorticity ( $\times 10^{-3} \text{s}^{-1}$ ). In this analysis, a closed circulation in the co-moving framework is evident at both 1.25 and 5.0 km above mean sea level. Saturation fractions near 0.9 in the vicinity of the disturbance's center [magenta diamonds in (top)] indicate convective activity within a region protected from external dry air intrusions. The maximum intensity of the circulation is at approximately 4 km above mean sea level. A rapidly increasing magnitude of the spatially averaged vertical mass flux below this altitude implies convergence of absolute vorticity in the lower troposphere. The presence of a moist, protected, convergent environment indicates that disturbance intensification is likely. On the following day, this disturbance became classified as Tropical Storm Karl.

checked, the dropsonde was inserted into the drop chute and ejected from the rear of the aircraft.

Once the data from the dropsondes had been quality controlled and processed via the ASPEN software, they were available for more detailed analyses. An additional ECS (Gjorgjievska) who worked in the operations center for five weeks analyzed the structure of each target disturbance as soon as each research flight concluded. This was done by performing three-dimensional variational (3DVAR) analyses on the dropsonde data. In light of the hypotheses that were tested during PREDICT (Montgomery et al. 2012), important fields to analyze or derive included the wind vectors in the co-moving reference frame; the



**FIG. 8. Airplane trajectory (thin dotted lines), simulated occultation tangent points (connected by thick black lines), and dropsonde locations (white circles) for PREDICT research flight 11. Shaded is TPW (mm) valid at 1200 UTC 5 Sep 2010, or near the start of research flight 11 (data courtesy CIMSS, University of Wisconsin). The area of interest on this flight is fairly moist but is surrounded by relatively dry air. During this flight, both the high (occultation paths 1 and 2) and low (occultation lines 3 and 4) moisture content areas were sampled by GISMOS. In conjunction with dropsonde measurements of moisture across the disturbance, these data may provide a better understanding of the temporal evolution of moisture fields in conjunction with developing and nondeveloping tropical disturbances.**

saturation fraction, or the vertically integrated precipitable water divided by the vertically integrated saturated precipitable water; the level of maximum circulation; and the levels of maximum vertical and horizontal mass fluxes. These products are illustrated in Fig. 7, where an analysis of the data from a mission on 13 September 2010 into what later became Hurricane Karl is presented.

Although the basic real-time analysis of dropsonde data discussed earlier is not unique to the experiences of ECSs in field programs, this sort of rapid variational analysis is not known to have previously been implemented in other field campaigns. During PREDICT, however, these preliminary diagnostics on the morphology of the observed disturbances were often taken into consideration by the PIs and mission scientists when planning and evaluating missions. Because multiple consecutive missions were conducted for most of the disturbances, these analyses provided a consistent way of illustrating the evolution of the developing, nondeveloping, and decaying disturbances.

**Water vapor measurements: GISMOS.** In addition to the four ECSs who served as DAs or data analysts, three ECSs (Johnson, Muradyan, and Murphy) were involved with the daily operation of another key portion of PREDICT instrumentation: the Global Navigation Satellite Systems (GNSS) Instrument System for Multistatic and Occultation Sensing (GISMOS), as developed at Purdue University. GISMOS collects radio occultation (RO) measurements of phase delay in GPS signals as the satellites set with respect to Earth. This delay is a consequence of the signal traveling through atmospheric layers of successively increasing refractivity. Because refractivity in the neutral atmosphere depends on temperature, pressure, and water vapor partial pressure, the phase delay can be used to retrieve vertical profiles of atmospheric water vapor and temperature (e.g., Kursinski et al. 1995).

GISMOS has flown in previous airborne campaigns to validate the instrument system in comparison with external measurements also collected during the flights. The PREDICT campaign, however, was the first science application of the GISMOS system. The goal of GISMOS participation in this campaign was to capture profiles of moisture at various formative stages in and around the hypothesized protected tropical disturbance environment. An example of such data collected during PREDICT is shown in Fig. 8.

During the PREDICT campaign, activity for the GISMOS ECSs was divided between working at the aircraft, both prior to and after the flights, and in the operations center. At the aircraft, it was necessary for a team member to prepare the GISMOS equipment for data collection before each research flight and, after each flight, to download, archive, and quality control the data. Given the large scope of the campaign, the amount of data being collected, and the fact that this was the first time the system experienced such usage, system maintenance was often an issue. Thus, the continual success of the mission depended on efficient and organized cooperation and communication between the GISMOS ECS team members and the GISMOS PI. At the operations center, one of the main duties of the ECSs was to monitor the quality of various GISMOS datasets such as the navigation data, RO data from conventional receivers, and data from the GPS recording system. For previous campaigns, this work was carried out back at Purdue University after the equipment's return from the mission. Having ECSs present for in-field postprocessing meant that the recording results from one mission could be evaluated and adjustments made prior to the following mission.

Additionally, the ECSs were given unique opportunities to work on the installation of new equipment, experience first-hand debugging processes, give feedback during serious discussions of system modifications and improvements, and take part in comprehensive collaborative problem solving. It was beneficial to interact with and learn from the GISMOS PI and NCAR aviation and support team in the face of problems in the field and precampaign installations rather than in a purely academic setting. Because the GISMOS PI was only present in the field during the first two weeks of the campaign, the ECSs were required to take responsibility for ensuring any problems were resolved quickly, particularly with the storage and transfer of the enormous quantity of data collected. The end result was a near 100% data recovery rate, excluding inertial measurement unit data from one of the 28 flights.

Their location in the PREDICT operations center also allowed the ECSs to take part in the daily weather briefings and agency discussions. The discussions in the operations center provided a real-time real-world classroom for the GISMOS ECSs with physics backgrounds to quickly gain the background and intuition that would have otherwise taken years in the normal classroom. The forecast discussions were often lead by fellow ECSs, adding an extra dimension to the learning experience by removing the subconscious hierarchical barrier to asking questions. Furthermore, the operations center was also a hub of continually updated information on the tropical systems targeted by PREDICT, which provided the GISMOS team with a unique opportunity to extend their knowledge of the underlying science of tropical cyclogenesis and the potential importance of integrating the retrieved RO refractivity profiles into numerical weather models.

*Conclusions and future research.* PREDICT proved to be a tremendous opportunity for ECSs. Conversely, were it not for the ECSs themselves, PREDICT as a whole would not have been nearly as successful. In this way, PREDICT exemplifies the benefits of a mutually beneficial arrangement between the organizing scientists and the ECSs involved: not only are the scientific missions of the field program able to be achieved, but the field is advanced not just by the data collected but also through the invaluable experiences gained by ECSs.

Throughout this article, we have highlighted a number of the ECSs' unique insights into PREDICT and how the field campaign has benefited them personally and professionally. For the GISMOS team

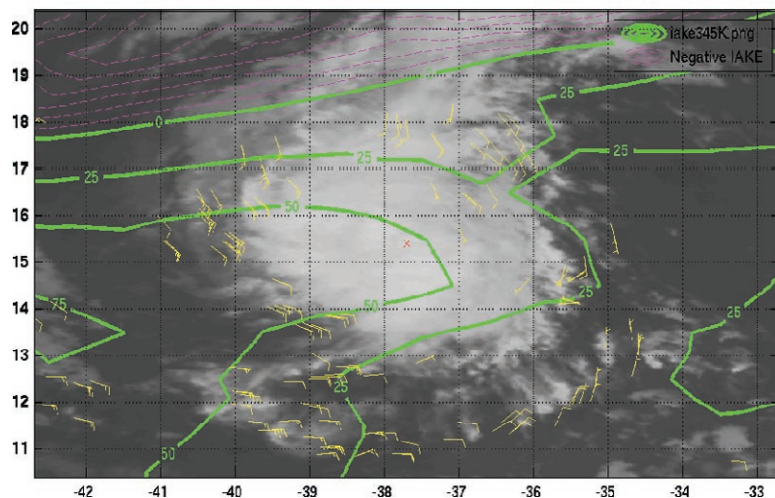
members, the problem-solving skills gained and meteorological knowledge acquired during their stay on St. Croix will serve them well in the graduate studies in the years ahead. For the others, the experiences were different yet the impacts still meaningful. One ECS (Cordeira) notes the following:

For myself, I believe there was a lot of insight and responsibility gained by being held accountable on a daily basis. The ability to make and contribute to forecast product generation and decisions that influence not only yourself, but a much, much larger contingency definitely fostered a unique two-week education and real-world experience, one that I'm not likely to forget anytime soon.

Similarly, another ECS (Riemer) notes the following:

For my future research it was particularly helpful that I had the opportunity to discuss the newly developed forecast product during our weather briefings. The numerous comments and questions from PIs and ECSs alike helped to clarify the strengths and weaknesses of the product and helped to focus my future research in this and new areas. As my research so far has made much use of numerical and theoretical models, taking part in research flights during PREDICT was an outstanding opportunity to observe and study cloud-scale processes and the interaction of scales in the real atmosphere.

As implied above, many ECSs have used or will be using data from PREDICT to form the basis for their master of science or doctoral degrees, or early career research. As part of his master of science research, one author (Sears) examined cases where a marsupial pouch existed in conjunction with an African easterly wave. His goal was to determine how upper-tropospheric conditions, such as characteristics of outflow layer ventilation [e.g., inertial available kinetic energy (IAKE); Fig. 9], can influence tropical cyclogenesis with such cases. The plethora of satellite-based products from the University of Wisconsin and flight observations collected during PREDICT provided him with an unprecedented opportunity to comprehensively analyze these features and their environments. The master of science research of another ECS (Monette) similarly focused on the evaluation of another satellite-based product, the previously discussed overshooting tops product, and its utility in forecasting tropical cyclogenesis and subsequent intensification.



**FIG. 9. GOES-East infrared satellite imagery overlaid with IAKE [contours; positive (negative) values in green (magenta)] valid at 1800 UTC 26 Aug 2010 on the 345-K isentropic level as derived from the NCEP GFS model analysis. Satellite-derived winds are displayed as barbs (half barb = 5 kt; full barb = 10 kt). The axes represent latitude ( $^{\circ}$ N) and longitude ( $^{\circ}$ E). IAKE can be a useful diagnostic tool for interpreting preferential conditions pertaining to the establishment of upper-tropospheric outflow channels. Flow toward high IAKE values can lead to more efficient ventilation and thus sustain conditions that promote the longevity of the deep convective activity believed to be necessary for TC genesis.**

Several of the ECSs who served as DAs during PREDICT are using the data that they processed and quality controlled as a part of their doctoral research. One ECS (Komaromi) is using the dropsonde data from developing and nondeveloping cases surveyed during PREDICT to better understand the environmental conditions distinguishing the two. Such work will include using these data to quantify model initialization errors and the sensitivities of the simulated tropical cyclogenesis process to these errors. For another ECS (Gjorgjievska), how convection and African easterly waves and their associated pouches are coupled forms the basis for her doctoral work. The data gathered from convectively active regions during PREDICT (e.g., Fig. 7) will prove instrumental in these studies. Similarly, those ECSs involved with the GISMOS instrumentation are utilizing the data gathered during PREDICT to better understand the four-dimensional structure of moisture at various formative stages in and around the hypothesized protected tropical disturbance environment.

There are a number of additional scientific questions that arose from some of the cases surveyed during PREDICT that are worthy of further study, some of which will undoubtedly be addressed by some of the ECSs involved in PREDICT field

operations. Such topics include—but are not limited to—the influences of monsoon-like surges off of South America to the development (or lack thereof) of tropical disturbances, such as may have been observed with Hurricane Karl during PREDICT; the potential role of Rossby wave radiation (e.g., Krouse et al. 2008) from Hurricane Igor to the formation of Tropical Storm Matthew during PREDICT; and determining whether other potential noneasterly wave, weakly baroclinic tropical cyclogenesis pathways exist within the tropical North Atlantic basin. In all, the experiences gained by ECSs during PREDICT have the promise of helping to shape their research directions and careers in the years to come.

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