9A.5 PROVIDING TROPICAL CYCLONE WEATHER SUPPORT TO SPACE LAUNCH OPERATIONS

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1. INTRODUCTION

Tropical cyclones (TCs) pose a significant threat to the Eastern Range (ER) and Kennedy Space Center (KSC), located on the Florida east coast. Thus the ER and KSC space launch programs must carefully plan for and quickly react to TC threats to protect both personnel and unique flight hardware, facilities, and other resources worth billions of dollars.

When a storm threatens ER and KSC personnel, assets, or operations the 45 WS provides detailed information to launch agencies on the threat of the storm including track, timing, intensity, and storm size, based on the National Hurricane Center's (NHC's) forecasts. This information is then presented to NASA and Air Force senior managers who decide if and when to begin actions necessary to protect resources.

This paper describes the process used by the 45 WS to provide TC forecasts to senior managers. Included are the typical NHC products used to "tailor" weather support for the customer, including the new experimental wind probability product. Also included are specific forecast concerns for the customers and several examples illustrating the 45 WS weather support for specific storms.

2. BACKGROUND

Weather has a large impact on many aspects of space launch, including: launch operations, ground processing operations in preparation for launch, post-launch operations, and various special missions. The 45 WS, within the 45th Space Wing (45 SW), is the United States Air Force unit providing this comprehensive 24/7 weather support to America's space program at Cape Canaveral Air Force Station (CCAFS) and KSC (Boyd et al., 1993). This support includes launch processing such as orbiter rollover from the Orbiter Processing Facility to the Vehicle Assembly Building (VAB), transport of the launch vehicle to the launch pad, movement of explosives, toxic chemical and fuel operations, launch operations including vehicle preparation and solid rocket booster recovery, and post-landing operations. Weather advisories, watches, and warnings are provided 24 hours a day for lightning, strong winds, severe weather, cold temperatures, and hail of any size.

The meteorological instrumentation used by 45 WS is one of the most unique and dense networks of weather sensors in operational meteorology (Harms et al., 2003). These sensors are needed because of the unique weather sensitivities of space operations, including ground processing, launch and landings, and the hazardous mesoscale weather frequently present in East Central Florida.

3. HURRICANE SUPPORT—THE PROCESS

The 45 WS forecasters are on duty 24/7 providing resource protection to CCAFS and KSC. When a TC develops in the Atlantic Ocean, Caribbean Sea, or Gulf of Mexico, the 45 WS monitors it and the NHC advisories closely. Forecasters post NHC advisories to the squadron's public web page and also email the advisory to customers to alert them of the latest storm information. The launch weather officers (LWOs) keep the launch vehicle processing personnel informed of the storm, as well. If a storm becomes a threat to CCAFS or KSC, the 45 WS coordinates with the KSC Weather Office to determine the potential impacts the TC may have on East Central Florida. Although senior leaders are informed about the potential threat to the region, joint KSC/45 SW meetings are sometimes needed to ensure the 45 SW Commander and KSC Center Director have all the details required to take the steps needed to protect resources. The senior leaders and their staffs then discuss what steps to take, if necessary, to prepare for the storm.

The 45 WS LWOs provide daily weather briefings to the Atlas, Delta, and Space Shuttle programs. During hurricane season, these briefings include an update on the tropics and any potential threats to KSC and CCAFS. The 45 WS evaluates tropical weather daily and notifies customers of any potential threats to launch vehicles or associated hardware.

If a TC has the potential to affect the spaceport, a Hurricane Condition (HURCON) may need to be implemented. HURCONs escalate the preparedness of each site from level 4 to 1 as the risk of 50-knot winds becomes imminent. Each HURCON level triggers implementation of checklists with specific hurricane preparation actions. The 45 SW Commander and KSC Center Director declare HURCONs for CCAFS and KSC, respectively. A HURCON declaration initiates checklists throughout CCAFS and KSC in preparation for a TC. The 45 SW and KSC coordinate their HURCON declarations to keep their actions consistent between the two agencies when the mission allows

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ensuring jointly used infrastructure is available for launch and ground operations. Many factors are considered when determining HURCON levels including maximum expected winds, timing of tropical storm and/or hurricane force winds; storm surge potential, and local and state emergency operations centers' sheltering and evacuation plans. The following HURCONs are used at CCAFS and KSC:

HURCON IV: 72 hours prior to the forecast arrival of 50-knot sustained winds
HURCON III: 48 hours prior to the forecast arrival of 50-knot sustained winds
HURCON II: 24 hours prior to the forecast arrival of 50-knot sustained winds
HURCON I: 12 hours prior to the forecast arrival of 50-knot sustained winds

In the event of an evacuation, 45 WS representatives transfer to the CCAFS/KSC Emergency Operations Center to provide weather support to the 45 SW and KSC prior to and during the storm. Weather support continues after a storm passes, as teams assess the damage to CCAFS and KSC. Weather support remains very important during this time to protect personnel working in an already hazardous environment while significant tropical weather may still be occurring. Additionally, this same support is provided to Patrick AFB, Jonathan Dickinson Missile Tracking Annex, and other remote locations such as Argentia, Newfoundland, Ascension, and Antigua in the event hurricane or other weather may affect critical operations related to a launch.

3.1. *Hurricane Training/Simulations*

Each year state and federal personnel participate in a hurricane exercise to prepare their agencies for the upcoming hurricane season. Using the simulated advisories provided by the NHC, 45 SW and KSC participate, rehearsing communication procedures and HURCON actions.

In addition to the state exercise, the 45 WS plans and conducts a special annual table-top hurricane simulation to prepare the KSC Space Shuttle Processing Division for the upcoming hurricane season. The table-top simulation is a low-stress environment and exercises the team's process to prepare for the season. During the simulation, the shuttle LWO presents a TC, advisory by advisory, to shuttle processing managers. For each 6 hour advisory, the Launch Integration Manager and Launch Director discuss and then determine the appropriate precautionary steps to take, including the proper timing to protect a shuttle on the pad as well as hardware located in the VAB or the Orbiter Processing Facilities. The simulation begins with a scenario representing the vehicle and facility configuration for the upcoming season. With this scenario, the launch managers determine the preparation time required for a storm. The team must first consider the NHC's historical average forecast errors, the probability of exceeding launch pad constraints, the risk of taking and not taking action, and the potential impact to the launch schedule and hardware before settling on a course of action.

3.2 *Communicating The Threat*

When discussing hurricanes or other hazardous weather with customers, 45 WS meteorologists present weather information in a clear, objective manner. The 45 WS presents the certainty of the weather threat by using probabilistic terms. For hurricanes, the probabilities describe the threat of KSC and CCAFS experiencing a certain wind threshold as defined by the customer. With this threat information, the launch vehicle managers can then determine actions based upon their accepted risk thresholds.

Shuttle Hurricane Information Form

HURRICANE KATRINA

Source: National Hurricane Center Advisory # 13, 26/1130L

Briefing Items:
1. Current National Hurricane Center (NHC) Storm Information - location, movement, strength
2. NHC Forecast Information
   - Characteristics of Storm and surrounding weather features
   - Storm path, speed, strength
   - Model Agreement
3. KSC Threat
   - Probability of 40 Kt Sustained Wind
   - Probability of 70 Kt Peak Wind
4. 40-Kt Wind Simulation

Current Storm Information: Source--National Hurricane Center (NHC)

Location:	25.1 N 82.2 W 205 deg @ 225 NM from KSC
Movement:	265 deg @ 6 Kts
Strength:	Winds: 85 G 105 Kts (Cat: 2) Pressure: 971 mb

NHC Storm Forecast: Based on attached NHC forecast plot of storm track.
- Forecast speed and intensity of storm at each point on attached NHC forecast:

Point	Current - 26/2030L	26/2030L-27/0830L	27/0830L-27/2030L	27/2030L-28/0830L	28/0830L-29/0830L	29/0830L-30/0830L	30/0830L-31/0830L
Speed	6 Kts	6 Kts	6 Kts	5 Kts	6 Kts	14 Kts	20 Kts
Wind	90G110Kt	95G115Kt	100G120Kt	105G130Kt	110G135Kt	35G45Kt	25G35Kt
40Kt Radii NE SE SW NW	70 70 40 30	70 70 40 30	70 70 70 70	80 80 80 80	90 90 80 80	0 0 0 0	0 0 0 0

The NHC forecast tracks Katrina northwest through the Eastern Gulf of Mexico. According to this forecast, Katrina makes landfall as a category 3 hurricane near Panama City on Monday, 29 Aug, ~1200L.

KSC Threat: Based on NHC's forecast, products, and published forecast errors.

Probability of 40 Kt sustained wind @ LC 39:	10%
Probability of 70 Kt peak wind @ LC 39 within 72 hrs:	2%

40-Knot Simulation: Note: This is a simulation. The official forecast is the NHC's current forecast.

Timing assumes Katrina follows the NHC forecast track for 24 hours, then turns clockwise and tracks NE toward KSC.

	Arrival Time at given storm speed					
Given Storm Speed	12 Kts	10 Kts	8 Kts	7 Kts	6 Kts	5 Kts
Time until arrival of 40 Kt winds	30 hrs	36 hrs	45 hrs	51 hrs	60 hrs	72 hrs
Date/Time of arrival of 40 Kt winds	27/1730L	27/2330L	28/0830L	28/1430L	28/2330L	29/1130L
	Sat	Sat	Sun	Sun	Sun	Mon

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Figure 1. Shuttle Storm Data Sheet. Developed by 45 WS to provide KSC Launch Managers detailed storm information directly related to shuttle rollback thresholds.

For example, NASA must roll the shuttle from the launch complex back to the VAB if there is a risk of 70-knot wind gusts at the launch complex, but the LWO does not determine the risk threshold and make the rollback decision. NASA managers know the full ramifications of a vehicle rollback including the additional risks of rolling back a Space Shuttle from the launch complex. The shuttle LWO presents the threat of 70-knot peak winds using probabilities derived from the probability product the NHC now provides with each

storm advisory. This information is coordinated between the 45 WS and the KSC Weather Office. Finally, the information is provided to the Launch Integration Manager and Launch Director, who ultimately decide whether to begin rollback actions. Actions to roll back a shuttle must begin a minimum of 48 hours before the arrival of 40 knot winds: 36 hours to prepare for rollback and 8 hours for the rollback. An additional 4 hours are also included to allow personnel to evacuate before exit roads flood. The vehicle must be rolled back before thunderstorm activity begins and before the onset of 40 knots sustained wind. Avoiding threatening weather before the storm arrives can add several hours to the overall rollback timeline. To provide the best information to shuttle managers, the 45 WS shuttle LWO provides a storm data worksheet which includes the current observed storm data, detailed information on the NHC's current forecast, probabilities of exceeding threshold constraints, and the timing of the rollback constraint wind given a worst-case scenario (Figure 1). This data sheet was developed in coordination with the Shuttle Launch Director to ensure the information covers NASA's requirements to make rollback decisions.

Using the worksheet and the probabilities ensure the storm threat is presented to the 45 SW and NASA in a consistent manner from storm to storm, and the managers clearly understand the risk that critical thresholds will be violated before actions are completed if they postpone decisions to wait for more data.

3.3 *Timing – When To Take Action*

The decision of when to begin protective actions depends on the forecast arrival of winds greater than a specific threshold. For shuttle rollback, the shuttle must be in the VAB before the arrival of 40-knot sustained winds. Thus, shuttle managers must decide at least 48 hours prior to the forecast arrival of 40-knot sustained winds when to stop launch processing and begin rollback actions. For instance, an approaching storm whose radius of 40-knot winds is within 300 nautical miles of KSC and is forecast to move at a rate of 4 knots would bring 40-knot winds in three days (75 hours). If, however, the storm's motion increased 4 knots, 40-knot winds would arrive in just 37 hours, thus reducing precious preparation time by a day and a half ("Hurricane Recovery," 2004). Additionally, there is risk of storms developing close to the East Central Florida Coast. During the 2005 hurricane season, several TCs including Franklin, Katrina, Ophelia, and Tammy, formed within 500 nautical miles of CCAFS and KSC, forcing decision makers to react quickly.

On the other hand, launch programs do not want to act too soon resulting in unnecessary, costly, and time consuming HURCON preparations and mission delays. Launch operations often continue as a storm threatens CCAFS and KSC. For example, Hurricane Emily developed during the 2005 hurricane season while KSC prepared to launch the Space Shuttle Discovery. The initial forecast looked ominous for KSC (Figure 2), but after monitoring the storm for several days, it was clear that Emily would stay well to the south of KSC and not be a threat to the shuttle on the launch pad. Due to the uncertainty and frequency of storms during a season, specific HURCON timelines and protective actions for launch vehicle hardware are prepared before hurricane season begins. These timelines not only help ensure launch vehicle managers accurately understand the time required for weather sensitive actions, but also allow them to wait as long as possible to gain confidence in the forecast track of the storm before beginning storm preparation actions.

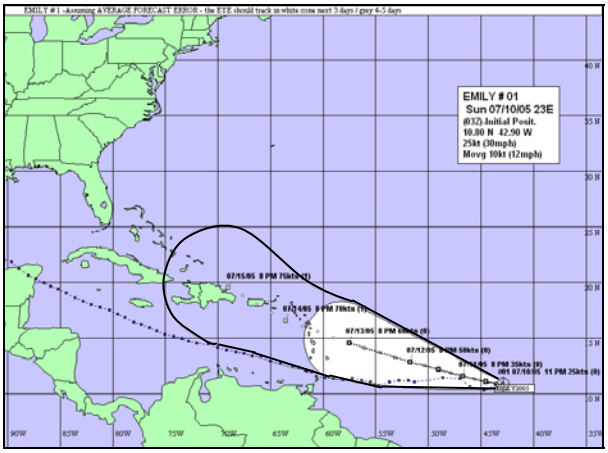

Figure 2. Advisory 1, Hurricane Emily. The Initial forecast ("Tropical Depression Five") looked ominous for KSC, but within a few days, it was apparent the storm would not threaten the Space Shuttle Discovery on the launch pad.

3.4 *Local Weather Data*

The 45 WS collects data from a large network of local weather sensors to conduct their weather support mission (Harms et al., 1998). Figure 3 displays the geographical distribution of key weather sensors. The Range Technical Services Contractor, Computer Science-Raytheon (CSR), archives this data (CSR, 2003), and the Marshall Spaceflight Center Environments Group also archives KSC data. Additionally, InDyne Inc., contracted by NASA, archives Spaceport Florida meteorological data in support of the Tropical Rainfall Measurement Mission, and provides the data via the World Wide Web.

After a TC passes through or near the area, the 45 WS reviews data collected from these sensors and provides customers with information concerning the winds, rain, and lightning experienced in the area. This information is critical to engineering studies to evaluate damage to facilities or flight hardware caused by the storm. The data is also used for planning the development of new facilities or structures and improving future preparation procedures. For example, in 2003, planning began for the refurbishing of the massive VAB doors at KSC. To accomplish this, the contractor designed a temporary door to replace each VAB high bay door as it was removed and refurbished. The 45 WS provided historical peak wind information,

including hurricane winds, to assist in designing the door. The squadron provided probabilities in a given year of exceeding certain thresholds which would drive the design of the temporary door. Given the weather information, the door was designed to a higher wind constraint than originally planned. In retrospect, the more robust design was essential given the peak winds associated with Hurricanes Frances and Jeanne in 2004, which occurred during the VAB door refurbishment project. Historical wind information, including winds associated with TCs, can help engineers design the appropriate structures given the risks of exceeding a certain wind threshold due to TCs and/or other significant weather.

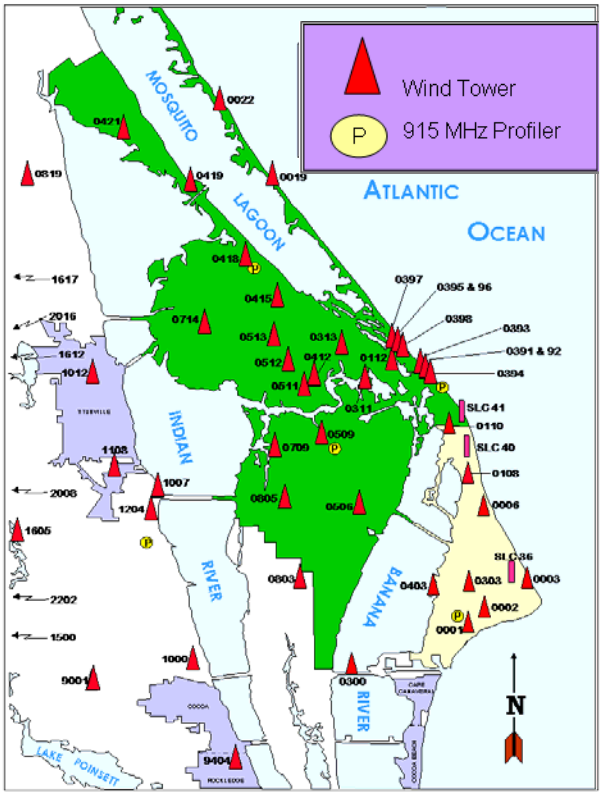

Figure 3. Locations of the 45 WS instrumented wind towers and 915 MHz wind profilers.

3.5 Improvements

The 45 WS is continuously improving weather support to their customers, including hurricane support. One method of doing this is through attendance at the various hurricane and tropical conferences throughout the year. This gives squadron members the opportunity to learn about new products and systems and to interact with different agencies, including the NHC. For example, during the 2004 season, Colorado State University began producing an experimental probability product which provides both graphical and text products depicting the probability of exceeding 34-knot, 50-knot, and 64-knot sustained winds at geographical locations within 120 hours of the NHC advisory time. The NHC incorporated this product into their Joint Hurricane Testbed project, evaluated the product and began using it on an experimental basis during the 2005 hurricane season, posting the products on their web site with the storm advisories. When this product was introduced at the Interdepartmental Hurricane Conference in 2004, the 45 WS recognized its relevance for objectively providing to the customer the probability of exceeding a specific weather threshold. As a result, the 45 WS began to evaluate the product during the 2005 hurricane season. During this season, several storms threatened vulnerable launch vehicles and sensitive shuttle marine operations. The 45 WS forecasters found the tool especially valuable as it provides a more objective method for producing probabilities of exceeding customer weather thresholds for a particular TC.

Although the new probability product proved useful to the squadron, some improvements are recommended. First, there is a need to define what percentage is considered a low, medium, or high probability for a given TC wind criteria using historical data. The reason is that a 15% chance for hurricane force winds at 72 hours may not seem that high to the general public or even senior leaders, at least at first glance. However, within the context of this tool, a 15% chance of hurricane force winds at 72 hours may constitute a high risk of occurrence for a given location and require earlier action based on this method. Second, there needs to be a method for including into the model the "confidence" the NHC forecaster has in the latest forecast. During the 2005 hurricane season, several storms developed in a weak steering environment and remained there for several days, most notably Hurricanes Franklin and Ophelia, yet the NHC probability product did not account for the initial low confidence in the first 36-48 hours of the forecast.

4. CASE STUDY: HURRICANE DENNIS 2005—SHUTTLE DISCOVERY EXPOSED

A prime example of a hurricane threatening a vehicle on the launch pad occurred in July 2005. Hurricane Dennis threatened the Southeast US while NASA prepared to launch STS-114, the Return to Flight mission after the Columbia accident. Although Dennis was not forecast to impact the KSC area directly, there was concern weather associated with feeder band activity could cause winds to exceed the 70-knot peak wind constraint for a shuttle at the launch pad. On Thursday, July 7, the storm forecast from the NHC and the models began to trend to the right, bringing the storm closer to the west coast of Florida, a path which could lead to a violation of the 70-knot peak wind constraint. Although the probabilities remained low, with such high consequences, shuttle managers began roll back preparations to stay ahead of the timeline for exceeding rollback weather constraints. As the NHC issued each advisory, the shuttle LWO briefed shuttle managers on the storm's status, NHC forecast, and model trend. Additionally, worst-case scenarios were presented to prepare managers for the highest possible

threat and earliest possible arrival of damaging winds. At midnight, Thursday night, 7 July, shuttle managers decided to stop rollback preparations and remain at the launch pad as the storm passed to the west. Hurricane Dennis passed 280 nautical miles west of KSC, and Complex 39B received 32 knots peak wind (Figure 4). In this case, detailed weather updates from the 45 WS and the latest information from the NHC enabled the shuttle program to prevent a schedule slip and avoid incurring additional risks of rolling back a vehicle.

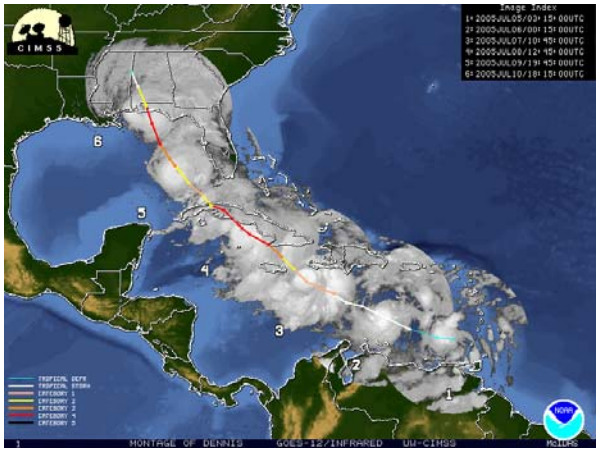

Figure 4. Hurricane Dennis mosaic, storm track and satellite (CIMSS, 2004).

5. CASE STUDY: HURRICANE FRANCES, 2004 – ATLAS LAUNCH

The launch of Atlas Centaur-167 was scheduled for 27 August 2004. On 21 August, a tropical wave emerged from the African coast, became a tropical depression on 24 August, Tropical Storm Frances on 25 August and Hurricane Frances on 26 August, one day before the scheduled launch. At this time, Hurricane Frances was located approximately 2100 nautical miles east-southeast of CCAFS. The first and second launch attempts on 27 and 28 August were scrubbed due to technical reasons; however, weather conditions were such that, had the count continued, weather launch commit criteria would likely have been violated through the launch windows, thus preventing launch.

After the second launch attempt scrub on Saturday, 28 August, Hurricane Frances was approximately 1675 nautical miles east-southeast of CCAFS. There was concern that the forecast unfavorable flow regime providing the Florida East Coast with late afternoon and evening thunderstorms would put subsequent launch attempts in jeopardy. Given two unsuccessful launch attempts and the continued unfavorable weather forecast, contingency planning was underway to prepare for a possible payload destack in the event the third launch attempt on Sunday, 29 August, was unsuccessful.

During the third attempt, launch commit criteria were violated approximately three hours prior to launch and persisted through the window resulting in a scrub due to weather violations. Hurricane Frances was located approximately 1500 nautical miles east-southeast of CCAFS. After the scrub, the payload customer requested daily planning forecasts for the period 31 August through 3 September. Wind probability forecasts were provided in daily telephone conferences to assist in the decision making process.

For the fourth attempt on Monday, 30 August, the forecast called for continued unfavorable steering flow with late afternoon and evening thunderstorms placing the launch attempt at risk of violating weather constraints. The fourth attempt was scrubbed due to thunderstorms and cumulus clouds as an outflow boundary interacted with the sea breeze. At that time, Hurricane Frances was located approximately 1275 nautical miles from CCAFS and was forecast to take a west-northwest track toward Central Florida. Weather planning forecasts continued to provide launch managers the probability of exceeding critical wind thresholds as a function of time to help them understand the risk of waiting beyond certain times to decide to destack and secure the payload prior to securing the range and evacuating personnel.

For the fifth launch attempt on Tuesday, 31 August, the forecast called for a gradual transition from the unfavorable flow regime with late east coast thunderstorms to easterly flow favoring thunderstorm activity over the interior and west coast. Through the countdown, steering flow gradually shifted from southwesterly to southerly. Although significant convection occurred over the mainland, the southerly steering flow and the easterly anvil-level flow held thunderstorms and associated anvils just outside of 20 nautical miles through the countdown with no weather constraint violations. Hurricane Frances was approximately 950 nautical miles east-southeast of CCAFS as AC-167 launched (Figure 5), the likely final attempt before a destack decision was required.

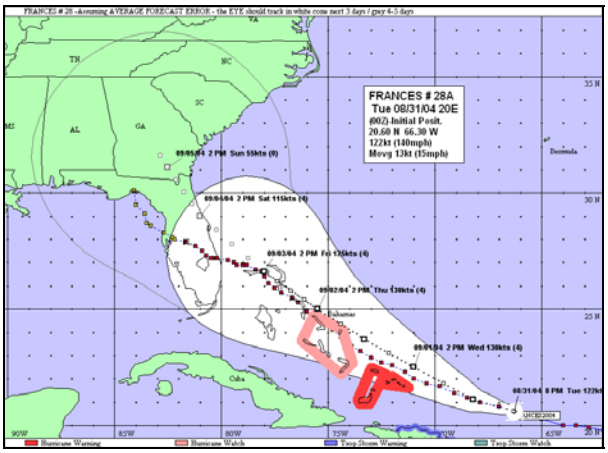

Figure 5. Hurricane Frances. NHC Advisory during the launch of Atlas-Centaur 167. The launch occurred after several days of launch scrubs, with Hurricane Frances becoming more of a threat to the vehicle on the launch pad each day.

Hurricane Frances continued its west-northwest track making landfall over the southern end of Hutchinson Island, approximately 80 nautical miles south of Launch Complex 36, on 5 Sep, 0030 EST, as a Category II hurricane (Figure 6). Wind probability forecasts during the five consecutive launch attempts were critical in supporting the payload community's decision to continue launch attempts or to plan for destack prior to winds exceeding destack constraints and forcing the payload to remain on the pad. AC-167 successfully launched on Tuesday, 31 August 2004 at 1917 EST. Eastern Range assets were secured and personnel evacuated on Thursday, 2 September 2004.

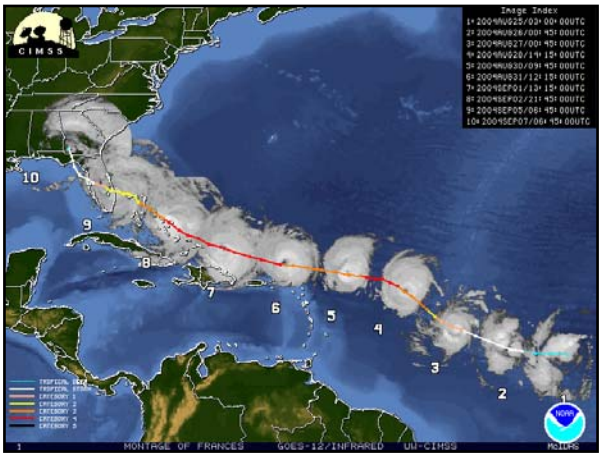

Figure 6. Hurricane Francis mosaic, storm track and satellite (CIMSS, 2004).

6. SUMMARY

The CCAFS and KSC space launch programs must carefully plan for and quickly react to TC threats to protect personnel, unique flight hardware, facilities, and other resources worth billions of dollars. Some protective actions are complex and weather sensitive, such as rolling the shuttle back from the launch pad, and must begin as many as three days before arrival of a storm's outer bands. The challenge is helping the customer determine what actions to take and when to take them. This requires assessing the storm's potential range of tracks, speed of movement, intensity, and radius of tropical storm and hurricane force winds; and communicating the resultant risk that customers' weather thresholds will be exceeded as a function of time. Many actions are very costly, shut down operations, and/or delay scheduled launches. However, the consequences of acting too late or too little can result in costly damage. Therefore, the 45 WS must carefully assess every TC threat and then clearly communicate the threat to launch operations at CCAFS and KSC.

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